C.F. von WEIZSÄCKER

CONTEMPORARY PHYSICS

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PREFACE

SOME time ago the publishers asked me to consider writing a survey of contemporary physics. They suggested a book which would introduce the educated layman, the sixth former confronted with a choice of career, and the student of allied fields to the problems of our branch of science.

Although I thought that such a book might well satisfy a certain need, I hesitated to undertake the writing of it, fully conscious as I was of the difficulties of the task. In no branch of science can a short survey of this kind be easy. If the amount of knowledge considered by humanistic studies might be likened unto a gigantic pudding to be consumed for the sake of getting at the plum, then in physics the corresponding work of preparation must be compared to boring through a layer of granite. Each one of us can partake of at least one bite of the incalculably large pudding of humanistic scholarship; granite, however, when the necessary tools are lacking, refuses to deliver the tiniest crumb. These tools are experiment and mathematics. Those who wish to explain physics without them are bound to feel like a conjurer who produces transitory illusions of a full stomach by his powers of persuasion. If my attempt was to have any sense at all it would have to awaken an honest hunger for more nourishing food. It would have to be an incitement to further study, in terms of which it would be merely a guide, a table of contents arranged in accordance with the inner laws of the subject.

It is for this reason that I have attempted to illustrate mainly the structure of physics as that of a coherent science. Relations which could not be explained in detail have been mentioned to indicate their proper place. Naturally, in all this, modern physics has been given special prominence, but since all its concepts are necessarily and objectively rooted in classical physics, it has been essential to discuss the latter also. Here a high-school knowledge of classical physics might help the reader; nevertheless, despite any confidence in this knowledge, may I advise him not to skip the relevant sections, for

it is just in them that we discuss the methodological problems which have led to our progress towards modern physics. Today even classical physics is viewed in a light different from that in which its originators would have thought possible.

I should like to take this opportunity of expressing my sincere gratitude to Dr. J. Juilfs for his devoted co-operation, without which the pressure of my other work would have prevented the writing of this book. His contributions have necessarily completed my more theoretical considerations, especially in the experimental and technical sections. About a third of the book was written by him, and the whole of it has been re-examined by him.

Goettingen.

C. F. von Weizsäcker.

INTRODUCTION

Chapter 1

WHAT IS PHYSICS?

THE following definition is attributed to Michael Faraday: "Physics is to make experiments and to publish them". Physics is rooted in experiment, in active, inquisitive and skilful intercourse with nature.

So profound a thinker as Faraday might be permitted the jest of considering publication as the sole contribution of pure thought to physics. In fact all experiments are blind if they are not guided, or at least interpreted subsequently, by theoretical considerations. The tool of conceptual thought in physics is mathematics, for physics treats of the relations between measured, that is numerically determined, magnitudes. Thus, side by side with experimental physics we also have theoretical or mathematical physics. In our century particularly it has again become clear that this kind of theory has philosophical origins and consequences.

Faraday's own discoveries gave the most important impetus to the creation of a third branch—Applied Physics. His discovery of electro-magnetic induction made electro-technics possible. From his field theory of electricity there developed, through Maxwell's mathematical treatment and Hertz's experimental realisation of the waves of these fields, both radio and radar.

Today the physicist is indispensable to any large industrial concern. He, unlike the engineer, is not required to work in a given field, but rather is he expected to give a reasoned answer to every new technical question by applying his knowledge of the fundamental laws of nature.

The separation of the three branches of physics is, to some extent, a necessary consequence of the division of labour. Nobody can master more than one trade equally well, especially when they are so diverse as mathematics and experimentation.

What is essential, however, for the progress of science is the collaboration of specialists and also of scientists of different nations. A theoretical school which is no longer interested in new experiments, just as a nation which thinks it can dispense with the scientific work of its neighbours, is damned to sterility. It may truly be said that the physics of our century has demonstrated more strikingly than anything else the value of co-operation, to all those who have participated in it. Perhaps the best example of the fertility of the union of different lines of research was the emergence of an entirely new branch of science, the quantum theory of the atom, when Niels Bohr fused the previously separate traditions of the English experimental school of Rutherford with the theoretical work of the Germans Planck and Einstein.

Amongst the natural sciences, physics occupies the central place. The word *physics* means nature, and thus physics in the original sense of the word is the study of nature in general.

Today we consider it as the theory of the general laws of nature, in contradistinction to sciences such as astronomy, geology, meteorology which deal only with specific phenomena. Chemistry, too, is a science of general laws. Atomic physics has reduced the difference between physics and chemistry to one of method alone. Today they are fundamentally one and the same science. In Chapter 12 we shall describe in greater detail the place of chemistry in the physical picture of nature.

What is not so clear today is the connection of physics with the other great realms of knowledge such as biology and the study of man. Physics is considered the science of material inorganic nature. How many profound philosophic decisions are inherent in this limitation, and how many who employ it are quite unaware of its significance and the problems involved! Descartes clearly distinguished matter as *res extensa*, i.e. substances that can be defined by their spatial dimensions, from consciousness which he called *res cogitans*. Contemporary atomic physics has not only freed the definition of matter from spatial dimension, but over and above this it has recognised that the concepts we use to describe atoms can only be basically defined by reference to certain observational situations, that is to acts of consciousness on the part of the physicist performing the experiments. It is perhaps the most important spiritual

contribution of contemporary physics that it has hinted at the need for changing our ideas on the relationships between matter and consciousness, object and subject, as they are found in the modern philosophic tradition. So long as we fail to do this, it is impossible to assign to physics its proper place in the sciences.

Furthermore, physics is not only knowledge, but a road to technological power. The greater the knowledge, the greater is the power. It is for this reason that the most penetrating, and what would therefore appear as the most abstract, branch of modern physics—atomic physics—has created the most terrible weapon ever designed by man. Here the question of the meaning and justification of all scientific endeavour is posed in deadly earnest.

I know of no straight answer to this question, and do not believe that there is one. The optimistic point of view that science, since it satisfies our deep-rooted desire for knowledge, can have only good consequences, seems to be contradicted by the facts. On the other hand, there seems to be no possibility of renouncing science because it has some bad consequences, for today science has become one of the material conditions of our existence. Through science and technology we have gained control over many of the conditions of our life, which were previously outside our influence. Now we must bear the responsibility for this and we cannot evade it without catastrophic consequences, even if we should wish to do so. It is just because this responsibility is so concrete, that we cannot state, *a priori*, the limits within which the use of science is justified and beyond which misuse begins. Basically this responsibility is of the same order as responsibility in the use of all the means given to us by nature. Man can use language for truth or for deception. This is his responsibility. Man can also use nuclear energy for his own benefit or for his perdition.

The individual has relatively little influence on the consequences of scientific discoveries, but he cannot escape them. It would be ostrich-like to shut our eyes to aspects of contemporary life in which these questions are posed. Facing them without self-deception is the first contribution which the individual can make towards developing the consciousness of this responsibility, both within himself and within all mankind.

Chapter 2

THE DIVISION OF PHYSICS

THIS book follows the traditional division of physics. This can be seen from the table of contents and need not be repeated here. The origins of this division are to be found in the historical development of the subject. The division partly derives from sense perceptions (heat, light, sound), partly from general concepts (mechanics, theory of relativity), and partly from the subject matter itself (electricity, atomic physics).

Here, before entering into the details of physics, we wish to ask whether a systematic division of physics is feasible today. This division would have to start with "elements" of which all other physical objects are composed. As a result of our search for such objects, we have arrived at some twelve "elementary particles"; see list on page 106 of this book. We can see that we must advance to the uttermost limit of the unknown in order to understand the structure of any known field. This is no paradox. It is an old truth that what is known immediately is not, in itself, simple. Aristotle had already distinguished between what comes first "for us" and what comes first "objectively". Thus, in any representation of physics, the same must hold true as in the reading of a book: the actual significance of the beginning can only be grasped when one has read through the whole. In our understanding of nature it is probable that we have not even learned to write the proper ending of the book at all. The great number of the elementary particles is probably to be understood from some common root which has so far eluded us.

According to a fundamental law of quantum theory these elementary structures, which we have called "particles" may appear as elementary fields or waves, under different experimental conditions. For our present purposes it is enough to consider only those which are stable, i.e. those which do not spontaneously change into other elementary particles. These can be classified into three main groups:

1—Matter	Proton, neutron, electron.
2—Electro-magnetism	Electro-magnetic field (photons).
3—Gravitation	The gravitational field.

The reader may notice that matter here appears under the names of "particles", while electro-magnetism and gravitation appear as "fields". This, too, will only be made clear when we come to the study of atomic physics. Here we merely wish to state the reason for these differences without, at this stage, explaining the concepts used: matter obeys "Fermi-statistics", electro-magnetism and gravitation obey "Bose-statistics". Elementary structures obeying Fermi-statistics offer a great resistance to compression in space. As a consequence of this, matter appears to be impenetrable, or as we say "*physical*". Bose-statistics does not lead to these limitations. Therefore, the electro-magnetic and gravitational fields do not have the property of impenetrability.

The Atom

The smallest discrete body that we speak of as "matter" is the atom. It consists of a nucleus composed of neutrons and protons and of a shell of electrons. The number of protons in the atomic nucleus determines the number of electrons in the shell, and hence the behaviour of the atom when it is brought into contact with other atoms. The laws governing this behaviour are those studied by chemistry. All visible bodies consist of many atoms. There are some properties which apply to all physical structures that can in any way be described as bodies (that is, composed of almost impenetrable atoms). The laws governing these properties are investigated by general mechanics: they are the laws of the motion of bodies. The causes of the motion are called forces. If certain forces are simply assumed as given, and the resulting motions are calculated, then we are working in the various special fields of mechanics, e.g. celestial mechanics, theory of elasticity, hydro-dynamics. Conversely, from the observation of motions, we can infer the existence of "fields of force" producing these motions. In this way gravitation and electro-magnetism were discovered.

Apart from motion, there are other phenomena observable

by the senses, such as light, warmth, smell, taste. All these can now be shown to be caused by matter and electro-magnetism (this obviously does not "explain" the process of perception itself—see Chapter 5). Light is shown to be a vibration in an electro-magnetic field, sound an ordered vibration of matter, and warmth a disordered movement of atoms. Smell and taste arise from chemical reactions.

Finally our ideas of space and time themselves, as the framework within which elementary objects exist, are not without problems. There are theories dealing with the connections between space and time and certain of the fields: with electro-magnetism in the special theory of relativity and with gravitation in the general theory of relativity. At present, matter, electro-magnetism, and gravitation cannot be deduced from one another.

PART I: MECHANICS AND ACOUSTICS

Chapter 3

THE FOUNDATIONS OF MECHANICS

MECHANICS deals with the motion of bodies. We can investigate either the processes of motion as such (kinematics), or the relationship between motion and the forces that cause it (dynamics).

Perhaps the most important achievement of those seventeenth-century physicists who developed mechanics (Galileo, Kepler, Huygens, Newton, Leibniz) was that they gave clear definitions of basic concepts such as "motion", "force", "mass". These definitions had to correspond to processes in nature, and thus they could not be discovered by pure thought. Conversely, fruitful experiments were only possible when reasonable questions could be posed beforehand. It is in this inter-connection between experiment and theory, each of which involves the other, that concepts begin to emerge more clearly.

Motion

Let us first look at motion. It is conceived as the change of place of a body in time. Conversely, rest means the remaining of a body in the same place.

What do we mean by "the same place"?

To the naïve man the earth is a "natural system of reference". My house always stands in the same place. A ship, a car moves from place to place.

The progress of knowledge has made this picture of unsophisticated absolutes only a relative one. Consider first the concepts of above and below, which in naïve concepts of space, are as obviously absolute as rest and motion: man's head is above. The earth, however, is a sphere. Do the inhabitants of the antipodes walk about with their heads below?—We learn: In space itself there are no privileged directions. "Below" means to us earth dwellers, the direction to the centre of the earth, wherever we might be on it.

This early relative approach which was already obvious to Aristotle, is the model of all later ones. The world picture of the earth occupying the central position of the universe, the Ptolemaic world picture, still formed a natural system of reference. However, since Copernicus it has been known that the earth moves. Is then the sun, perhaps, absolutely at rest? Since Giordano Bruno the idea of an infinite world has gained headway; all stars move with respect to one another. How then could one find an inert system of reference?

Here there was a choice. We could conceive of place, rest, and motion purely as concepts of relations. This is what Leibniz wanted to do. One then says: this body is at rest compared with that other body. There is as little sense in saying it is "inherently" at rest as it is to say that "inherently" Europe is above and Australia below.

Instead of this concept, Newton introduced the idea of absolute space "in" which bodies moved. Thus for him space itself was a reality. Newton, the physicist, demanded that reality must have effects by which it could be empirically recognised. In this "bucket experiment" (*see* page 92) he wanted to observe the effects of motion "relative to space". The problems involved will be discussed later on, in connection with the general theory of relativity. Here we must leave open the question of the precise meaning of Newton's ideas, and whether they were right.

It may appear unsatisfactory that even in the definition of the most simple concept, a decisive question must be left open. We must get used to this procedure, for it is just in this way that physics proves to be a science not of invented things, but of reality. Every concept depends on every other one. Thus, even the most simple concepts can only be formulated clearly when we have knowledge of all the other concepts. In the meantime, we must therefore begin with tentative and deliberately undefined concepts which we must be ready to revise with every advance in knowledge. Each such revision is no revolution but only a clarification, so long as we remain conscious of the impermanence of our first attempts. That physics is scientific is not only shown by the exactness of its concepts and statements, but also in its awareness of the limits which, at any moment, are set to this exactness.

The tentative nature of the concept of motion is shown by the fact that at the outset a system of reference for measuring position and motion can only be established for each case separately. For most measurements on earth, the earth itself will serve as such a system of reference.

Physics is a quantitative, a measuring science. How shall we assign a numerical value to motion?

A car is driven at 72 km (45 miles) per hour. This numerical value we call its speed. It gives the number of units of length which are traversed in one unit of time. As basic units for connecting these different kinds of magnitude, the physicist usually chooses the cm (centimetre) and sec (second). Our car goes 7·2 million cm (in short $7{\cdot}2.10^6$ cm) in 3600 sec ($3{\cdot}6.10^3$ sec), i.e. 2000 cm/sec or, to give us a better picture, 20 metres per second.

Speed can change with time. A car which does 72 km in one hour, does not traverse 20 metres in each second. Through villages it will probably go at only 5 metres per second, on a straight road however, it may do 30 m/sec. By the "speed" of a body the physicist understands its instantaneous speed. What is that?

Speed is the ratio of distance to the time in which this distance is traversed. When the speed does not change during this time, we obtain the same ratio if we consider half of the original distance, for this is traversed in precisely half the time. Correspondingly, a quarter of the path is traversed in a quarter of the time; the ratio of the two magnitudes remains the same. It does not change even if we take ever smaller distances and times ("small differences" or "differentials"). The speed at any moment is the limiting value which the ratio of distance to time assumes if we take very small values of distance and time: the "differential quotient of distance and time".

This limiting value can generally be obtained even if the speed changes with time. In most cases we can find an interval so small that the speed does not change in it. In an hour a car may travel at many different speeds, but generally during one second the speed changes only imperceptibly. Even if the brakes are applied sharply, the speed will change only by little within a thousandth of a second. If we consider even smaller time intervals, the speed in them will be practically

constant, and thus we shall obtain a certain number giving the speed at each moment.

The change of speed with time can also be measured. This is called acceleration. A body falling freely increases its speed every second by about 10 m/sec. Its acceleration therefore, is 10 m/sec per second or, as it is written, 10 m/sec^2. If it starts from rest, it would have the speed of 10 m/sec after one second, 20 m/sec after two seconds, etc. Let us consider the first second more carefully. At the beginning the speed was zero, at the end 10 m/sec. In the meantime, speed has been increasing uniformly. In the first second it therefore has the average value of the initial and the final speeds, i.e. 5 m/sec. In the first second it will therefore fall 5 m. Equally, in the second second, it has an average speed which lies halfway between 10 and 20 m/sec, that is 15 m/sec. In the second second it falls 15 m, and therefore 20 m in the first two seconds together. This is an elementary explanation of the calculation of the motion of a falling body first made by Galileo and then confirmed by experiment.

Thus, acceleration too has just been conceived of as something momentary. Mathematically it is the differential quotient of speed and time.

Scalars and Vectors

Speed not only has a numerical value, but a direction also. A magnitude which can be simply characterised by numerical value, i.e. by a number, is called a scalar (because it can be read on a scale). Temperature, shown by a thermometer, is a scalar. A magnitude which, apart from its numerical value has a direction, is called a vector (from *vehere*=transport). An instance of a vector is the distance from London to Manchester; it can be given by a numerical value, the distance (in this case about 182 miles) and a direction (here: along the surface of the earth approximately NW).

A vector can be characterised by three numbers. We have just given three data for the vector London–Manchester: its numerical value, a flat surface in which it lies (roughly the surface of the earth), its angle with the north direction (NW). Instead of this we can take as the origin of the vector, the origin of a rectangular system of co-ordinates. Then the

position of its final point is characterised by three co-ordinates x, y, z. These numbers also determine the vector; they are called its components. In the choice of components there is an element of arbitrariness. The co-ordinate axes could be orientated differently. In order to stick to our example, in London we could choose the x-axis towards the east, the y-axis towards the north and the z-axis perpendicularly upwards; equally well we could take the x-axis in the London–Manchester direction, the y-axis at right angles to Bournemouth and the z-axis again to the top, or any other orientation at will. According to the choice of axes, the components of one and the same vector are changed. If we always state to which system of co-ordinates the respective components refer, there will be no confusion. This may serve as the simplest of examples for the dependence of our physical data on the position of the observer.

The distance London–Manchester exists in nature without a system of co-ordinates, but without such a system it cannot be fully characterised. However, we have a choice of co-ordinate systems. Thus, in general, we can speak of reality at any given moment only in one language. However, something is added to reality, for there are many languages and we can change the language we use. Confusion can be limited if we know which language we are using. It would be just as senseless to quarrel about the "true" components of a vector, as about the "true" name of that animal which we call "dog".

Acceleration too, is a vector. A velocity can be increased, decreased, diverted to the left, to the right, to the top, to the bottom. All this is classified by physics under the general heading of "acceleration". In the way that we formally represent a body at rest as having a "motion with zero speed", so we can call deceleration an "acceleration" whose direction is exactly opposite to that of the corresponding velocity. Even though there is no change in speed when the earth describes an (almost) circular path around the sun, this is still "accelerated" motion. For though the numerical value of the speed of the earth always remains the same, its direction is constantly changed. The vector of acceleration in this case is always directed towards the sun.

We could show that the three components of the vector

of acceleration are precisely the differential quotients of the corresponding vector components of speed with time.

Force and Mass

Newton's Laws of Motion are:

1. Every body continues in its state of rest or of uniform motion in a straight line except in so far as it is compelled by external impressed forces to change that state (The Law of Inertia).
2. Rate of change of momentum is proportional to the force applied (Force = mass × acceleration).
3. The mutual actions of any two bodies are always equal and oppositely directed (Action = Reaction).

Of all the concepts of physics, the concept of force is one about which discussion has raged the longest. It formalises ideas of the causes of motion. What was needed to clarify this concept was the removal of all those ideas which referred to particular situations only.

An excellent rationalisation of everyday experience can be found in the Aristotelian conception of the causes of motion. According to it, every body has a "natural place": a heavy body such as a stone, below; a light body, such as air or fire, above. A body, which is not in its natural place always tries to regain it. This is one of the possible causes of motion. Another is a constantly active force: wind driving the sailing boat, a horse pulling the cart. All earthly bodies not acted upon by any causes of motion, are at rest.

It was the greatest achievement of Galileo that he dared to challenge everyday experience by saying that a body on which no force is acting is either at rest or in uniform motion. Put into modern language: its velocity remains constant. This "uniform motion" has, strictly speaking, never been observed up to date. We express this in the following way: some force is always acting on every body (mostly friction and gravity). But the smaller the force, the nearer does the motion approach the ideal type of uniform motion.

This statement of Galileo proved itself by its fruitfulness.

It enabled us to measure forces through the deviation from uniform motion. This takes place according to Newton's second law.

The "magnitude of motion" (or, as we say today, the "momentum") which concept is used in this law, is defined as the product of the mass of a body and its velocity. This magnitude is a vector whose direction is equal to the direction of the velocity. If we compare different bodies of equal velocity, then their momenta are proportional to their masses. Two equal bodies of equal velocity have, taken together, double the momentum of each separately.

If the mass of a body is constant then the change of its momentum with time is equal to the product of its mass and its acceleration. This magnitude, according to the second law, must be equated to the external force working on the body. If there is no force, the acceleration is zero and we come back to uniform motion. The greater the force, the greater the deviation from uniform motion. However, the body resists any alteration in speed through its "inertial opposition". The greater its mass, the smaller the change in velocity for any given force.

We have just established a mathematical relationship between force and mass, without having defined either concept very clearly. This being the case, the question arises how this law can be put to an experimental test at all. Given a body in any environment, how can one determine its mass and the forces working upon it? In the final analysis only by means of Newton's second law. How can one then, in turn, test the validity of the law with the magnitudes thus determined?

We have to learn that this state of affairs is not a bad one, but that it is merely an example of what happens when we test any newly propounded basic law. Only the new law itself generally leads to a clarification of concepts which, in turn, are used to test the law. This test does not consist of a single experiment (there is hardly ever a "crucial experiment" in favour of a theory; at best, only against a theory), but rather do we investigate whether the law enables us to express a whole number of observable facts simply and to predict them.

In our example, the facts are on the one hand Galileo's observations of fall and throw, and on the other hand, Kepler's

empirically verified laws of the motions of the planets. At the end of the paragraph on motion we explained that, in free fall, acceleration is constant. This must now read: the force is constant. The simplicity of this law is the greatest spur to further investigations. Finally we find that every body can be assigned a number—its mass—which measures its resistance to the action of the different forces. Further, every physical situation into which a body can be placed may be assigned a vector—the force—as a measure of the acceleration acting on the body. From the character of force as a vector there follows (this is by the way) the law of the Parallelogram of Forces: all forces must, if Newton's second law is true, be capable of being composed just like accelerations. For them as for all vectors, the parallelogram construction is valid, which may be expressed arithmetically: vectors are added by adding their components.

Let us summarise: mass and force are defined as magnitudes characteristic of certain bodies, and obey Newton's second law. The correctness of these axioms follows from the fact that in innumerable practical cases, it was the only assumption capable of bringing simple order into a chaos of experiments. Its usefulness is shown in technology: only machines constructed with its help, work in the predicted manner. This situation may appear unsatisfactory from *two* points of view. The procedure of proof does not proceed deductively from clearly formulated hypotheses, and secondly, the "essence" of force and mass still appears hidden.

The demand for a deductive structure, however, would be misguided. Physical science, however precisely formulated, is not gained any differently from other forms of knowledge referring to experience. We cannot start at a given point and from it deduce all others. We can only learn through long acquaintance with reality. A physical law, like a light shone into a dark room, is proved only by the order which it reveals.

The other objection led to persistent attempts throughout the centuries to "explain" inertia, mass and force. Thus, it was believed that all forces should be reduced to pressure and thrust, that is to the impenetrability and mobility of matter assumed ex hypothesi. All these attempts have remained unsuccessful and contemporary atomic physics proves them

hopeless. We may say that they are due to a lack of methodological understanding. To "explain" may either mean: to make transparent—this is done by the Galileo–Newton theory for the phenomena of motion—or it may mean: to refer something to something else. But then the other must either remain an unexplained hypothesis, or in its turn, be reduced to a third thing.

What do we demand of a basis for explanation? Hardly that it re-asserts what is to be explained in a different way. It was Galileo's achievement to look "behind" appearances, and to accept the striking simplicity of the laws in place of perceptual evidence. The theory of pressure and thrust, however, always seeks invisible processes which take place according to visible ones; it establishes a quasi-appearance behind observed phenomena. Today we say: those who want to make a perceptual picture of the world must follow Goethe and make do with true appearances, i.e. with the original phenomena. Those who wish to look behind appearances should not try to re-establish here the laws of those realms which they endeavour to leave. Perhaps atomic physics will be able to reduce Newton's laws to more basic, but certainly not to perceptual ones.

Energy

If we raise a body weighing 1 kg through 5 metres, we must do a certain amount of work *W*. If we raise four bodies of the same weight, through 5 metres each, we must do four times the work *W*. If instead, we raise the single body four times, each through 5 metres, i.e. 20 m altogether, we must again do four times the work *W*.

If we let the body drop from a height of 5 metres, it arrives below (if we neglect the resistances of the air) with a velocity of 10 m/sec. Leibniz assumed, that in this motion, in its "living force" (*vis viva*), or as we say today, in its "kinetic energy", there was hidden the exact equivalent of the work which had been used for raising it. Obviously, kinetic energy must be proportional to mass, for the four-fold body required a four-fold effort of work in raising it. Is momentum perhaps a measure of kinetic energy? Leibniz realised that this was not the case. Momentum is proportional to velocity. The body that falls

from a height of 20 m has (*see* page 22) double the speed of one falling from 5 m. To raise it, four times the work was needed. Thus Leibniz put kinetic energy proportional to the square of the velocity. It can be shown that this always corresponds with the law of falling bodies.

The work done on the body has, through its kinetic energy, become manifest. Previously it was "hidden" in its position in space, in the fact that it was raised. We have become used to speaking of "energy of position" or of "potential energy" (in other words, energy which may manifest itself in its kinetic form).

From Newton's laws the following can be derived: the work which is done on a given body is equal to the product of the force applied to the body and the distance through which the latter has moved. If the whole of the work can be regained by returning the body by any path to its point of departure, we can define a potential energy (U) which is only dependent on the position of the body. If further, kinetic energy is defined as half the product of the mass and the square of the velocity ($T=\frac{m}{2}v^2$), then there applies the law of the conservation of energy: $T+U=const$; in words—the sum of the kinetic and potential energies of a body is constant. In this form, however, the law is not generally valid. For instance, a body can come to rest through friction. Here kinetic energy is lost without changing into potential energy. The corresponding work cannot be regained.

Newton's third law can also be related to the law of conservation of energy. It deals with a process which we have not expressly discussed yet: the interaction between two bodies. From Newton's third law it follows that the centre of gravity of two bodies, on which no further external forces are acting, obeys the law of inertia: it stays at rest or in uniform motion. If this were not the case, these two bodies, on which no external forces are acting would, under the influence of their own mutual forces, be able to execute accelerated motion with respect to their environment. In this case, the total energy would not be conserved.

Chapter 4

SELECTED TOPICS IN MECHANICS

Statics and Centre of Mass

STATICS is concerned with the conditions under which a body is in a state of equilibrium, or at rest. It is not concerned with the change of shape of bodies due to external forces: all bodies are assumed to be rigid. Statics looks for the conditions of equilibrium by composing the forces applied to a body according to the law of the parallelogram of forces, or when necessary, by resolving these forces. The geometric sum of all those forces which are applied to a body, is called the resultant force. Equilibrium of forces, therefore, exists if there is no resultant force.

In practice, gravity acts upon every body on the earth. In the simplest case it can be measured with a spring balance, in which the extension of the spring is a direct measure of the force applied, the "weight" of the body. If a body, acted upon by gravity, is to stay at rest, another suitable force must oppose gravity. In the case of our spring balance, this is the elastic force of the spring. In general, gravity is opposed by those elastic forces which are produced by a distortion of the supporting medium. This is generally neglected in practice. Constructors of buildings and bridges make use of the inherent properties of materials, and of the law of equality of action and reaction only.

Since, according to Newton's laws, rest is only a special case of inertial motion, so statics is only a special application of the general study of the equilibrium of forces under which the uniform motion of bodies is possible. If the external forces acting upon a body (or upon a system of bodies) are in equilibrium, its centre of mass is subject to the law of inertia: the momentum of the whole body or system is constant. But if a part is displaced within it, i.e. if this part should acquire an additional momentum, the rest must be given an opposite and equal momentum—in order that the momentum of the total

body or system remain constant. The velocities of both parts are at every instant inversely proportional to the masses.

An application of this law of "the conservation of momentum" is rocket propulsion. A gas, which is brought to a high pressure inside the rocket, would press on all parts of the walls equally, if the rocket were closed. The elastic forces of the walls would exert a pressure equal and opposite to that of the gas: the rocket would stay at rest. If, however, the gas can stream out of the rocket in one direction, then according to the law of momentum, a motion of the rocket in the opposite direction will take place, so that the common centre of mass of the gas and rocket stays at rest. If the rocket were already in motion before the expulsion of a particular volume of gas, the centre of mass would retain this motion. The rocket is thus constantly accelerated in the same direction through the continuous expulsion of gas. The popular conception that the rocket pushes against the surrounding air is false. In thin air, or even in interstellar space, the gas can stream out more forcefully, and the rocket would work even more effectively.

Stellar Mechanics and General Particle Mechanics

The field in which classical mechanics was first applied was that of the motion of the planets. The decision between the opinion of Aristotle and Ptolemy that the earth is at rest whilst the planets revolve round it in "epicycles", and that of Aristarchus and Copernicus that the sun is the centre at rest of a planetary system, and the earth itself is a planet—this decision could not be made by means of kinematics alone. The motion of a set of many bodies can always be described by assuming any one of them at rest and considering the paths of the others as seen from it. Only dynamics could decide between the two rival pictures. Only in Copernicus's picture can the motions of the heavenly bodies be derived easily from simple assumptions about the forces acting between them. This application of mechanics to the heavenly motions, which up to then had been treated only geometrically, was also the beginning of a unified "physical world-picture".

Kepler, on the basis of the exact observations of Tycho Brahe established three empirical laws of planetary motion:

1. The planets travel in elliptical orbits, the sun being at one focus.
2. A line drawn from a planet to the sun sweeps out equal areas in equal times.
3. The squares of the times of revolution of different planets are in the ratios of the cubes of the major axes of their orbital ellipses. That is,

$$\frac{(\text{Length of year})^2}{(\text{Mean distance from sun})^3} \text{ is the same for all planets.}$$

Newton was able to derive these three laws by assuming that the attractive force of the sun on a planet is inversely proportional to the square of their distance apart. Motion is the result of the joint action of this "gravitational force" and of the resistance due to the inertia of the body (which can also be called a "centrifugal force"). Gravitation alone would simply pull the planet directly into the sun, inertia alone would let it escape uniformly into the infinite. In the true orbit it is constantly directed by gravitation towards the sun, and away from the path for inertia alone.

Newton further established the law of general gravitation: every portion of matter in the universe attracts every other portion with a force which is directly proportional to the product of their masses and inversely proportional to the square of their distance apart. This law explains both the motion of the planets, the fall of a body on to the earth, the motion of the moon around the earth, tidal motion (the result of the attraction of the moon on the sea), etc. In more recent times we have been able to confirm the law within all known cosmic space. It explains why binary stars follow elliptical orbits around each other, why clusters of stars and galactic systems keep together, and why there is rotation of stars and gaseous masses about the centre of their particular systems. We thus know the reason for the spiral structure of the greatest cosmic objects known—the spiral nebulae.

The law, however, requires a slight correction to Kepler's laws. The planets are attracted not only by the sun, they attract each other. Thus they deviate from the Kepler orbits. From the calculation of these deviations, a very complicated

mathematical theory has emerged in which many methods of general mechanics were originally developed. It is known that calculations of future astronomical events, as for instance the eclipses, belong to the most exact and best-confirmed predictions of physics.

Thus, this theory is interesting from the general point of view, that it has given rise to the concepts of "point or particle mechanics". The diameters of heavenly bodies are so small, compared with their distances from one another, that for many calculations they can be considered as masses concentrated in points, so-called "mass points". Thus, for a system consisting of mass points which act upon one another with forces depending only on the distance, we can state a number of general laws. For instance, we can say that these systems also have a centre of gravity which executes uniform motion in the absence of external forces. Furthermore the law of the conservation of energy applies to the sum of the kinetic and potential energies of all mass points of such an isolated system.

In point mechanics a concept has been developed which we shall use frequently: that of the degrees of freedom. We say a mass point has three degrees of freedom, by which we mean that its position is characterised by three numbers (e.g. its three co-ordinates in a system of perpendicular co-ordinates). The mass point is free to alter three numbers by its motion. Correspondingly, two mass points together have six degrees of freedom, since each has three co-ordinates; the condition of a system consisting of two points at any moment is therefore characterised by six numbers. Three mass points have nine degrees of freedom and so on. The more degrees of freedom a system has, the more difficult it is to describe its motion. Pieces of machinery should, in general, have only one degree of freedom, such as for instance, the revolution of a wheel which determines all the other motions of the machine in an unequivocal manner.

Point mechanics has played an important role in the development of the physical world picture. The apparently immediate force of gravitation acting between one body and another some distance away, seemed at first sight most mysterious; it was thought to require further explanation at the time of Newton, when physicists helped to explain every-

thing by pressure and thrust. Newton's famous sentence "*hypotheses non fingo*" ("I don't invent any unprovable contentions") rejects speculation about this "explanation", not because Newton thought all attempts at explanation were basically senseless, but because at the time there was no possibility of testing such explanations. A hundred years later (probably starting with Boscovich) people had become so used to the idea of "forces acting at a distance", that an atomistic explanation of nature, the smallest units of which were mass points, acting upon each other through such forces, seemed acceptable. We shall see how the contemporary physics of fields and atoms has outgrown even these concepts.

Oscillations

A body hanging on a spring is constantly under the influence of an "elastic" force. It has a position of rest in which no resultant force acts upon it. If it is moved from this position of rest, a restoring force acts upon it, and tries to bring it back to this position. If the distance of the body from the position of rest is not too great, the restoring elastic force is proportional to the distance. A body displaced by 2 mm from its position of rest, is then pulled back with twice the force experienced by a body displaced by only 1 mm.

Forces not due to the elasticity of the bodies, but nevertheless proportional to the distance from a position of rest, are called "quasi-elastic" forces. Thus, for the case of a pendulum with a sufficiently small displacement to the side of its position of rest, gravity acts as a quasi-elastic force.

Under the influence of elastic or quasi-elastic forces bodies can perform oscillations. At first the body may be in a position of rest. If we let a force act upon it for a short time (i.e. if we give it a slight impetus) we should set it in uniform motion if it were freely movable (as in the case of a billiard ball). However, here is a restoring force acting upon it, and the further it moves from the position of rest, the slower does the motion become, until finally, after reaching a maximum displacement, the so-called distance of swing or "amplitude", the body changes its direction of motion. At this point the kinetic energy of the body becomes zero, and the potential energy has its greatest value. On returning, when the body again reaches its

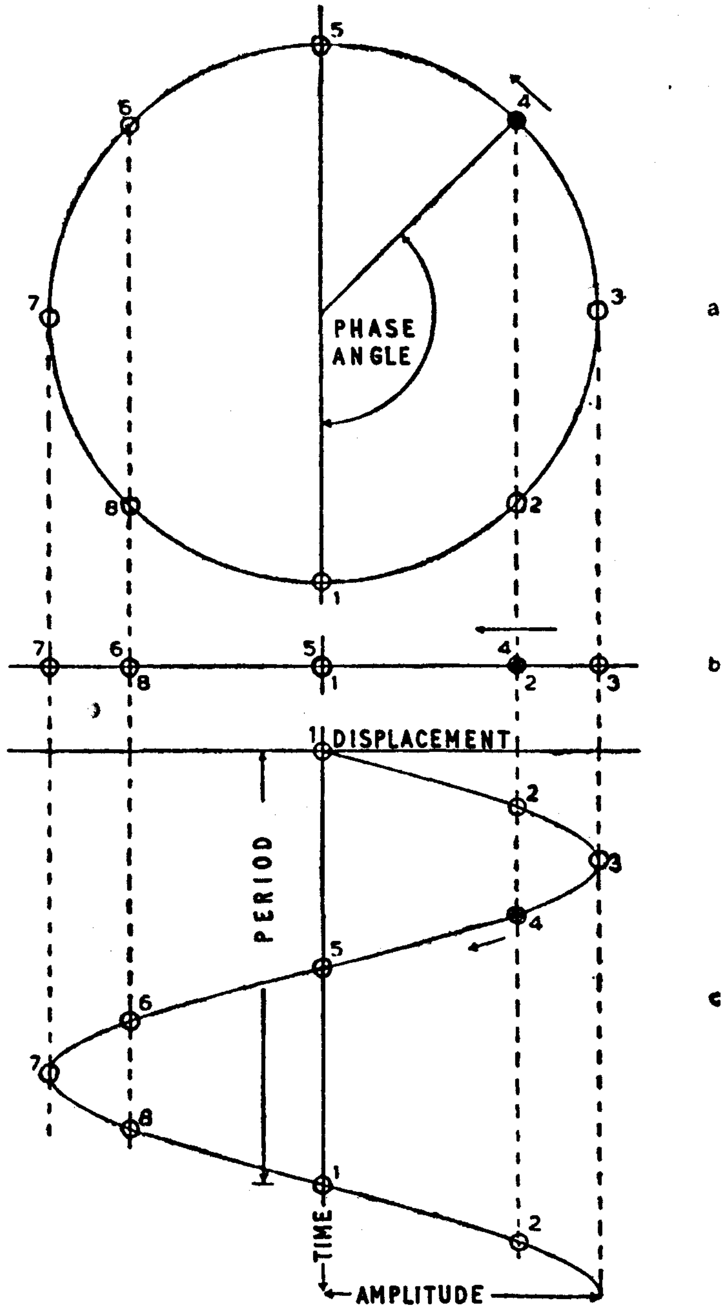


FIG. 1. Harmonic oscillations. (*a*) A point moving on a circle with constant velocity. (*b*) Simple harmonic motion. (*c*) The dependence of the displacement from rest on the time.

original position of rest, its speed takes on a maximum value, the potential energy has changed into kinetic energy, and the body swings beyond the position of rest to the same distance on the other side, back again, and so on (unless its motion is further impeded by friction, and if it does not suffer any further "damping").

Uniform rectilinear motion is represented mathematically by the motion of a point on a straight line with constant speed; so-called simple harmonic motion can be represented by a point moving at constant speed in a circle, and the projection of this motion on a horizontal line (which mathematically is nothing else than the well-known trigonometrical sine or cosine function) represents the actual oscillations (*see* Fig. 1). To a full circle there corresponds a complete oscillation. The angle between the radius to the moving point and some fixed radius—for instance that to the point corresponding to the position of rest—is known as the "phase angle"; the phase angle at time "zero" is called in short the "phase".

As we shall see later on, the expansion of a solid body means that the particles of which it is composed experience a pull in the direction of expansion, greater than when the particles are at rest. If there are no rearrangements of the relative positions, the inner forces of attraction will oppose the force of expansion (elasticity). If the force of expansion ceases to act, the body oscillates internally about its own position of rest, although there is considerable damping because of friction. In technical tests on the properties of materials, we investigate, *inter alia,* the limits of tension or torsion up to which there is no rearrangement in the structure of the material and where the elastic forces are still acting, and beyond which the material would either become deformed or even break.

It is due to these internal forces that a string or a membrane will oscillate if it is displaced from its position of rest. In doing so, it produces oscillations in the surrounding air by compressing it during its motion. The air which is compressed near the membrane compresses the air next to it, and in this manner the compression is propagated further and further into space. In the meantime the membrane swings back and reduces the pressure in the air in contact with it. This rarefaction, too, is propagated in an analogous manner through the surrounding

space. Thus, starting from the membrane, a sequence of pressure maxima and minima travels through space in the form of a wave which impinges upon objects in its path—for instance, the ear-drum of the human ear. This state of oscillation spreading through space is called a "wave". The distance in space between pressure maxima (or minima) depends upon the material in which the wave is moving and is called the wave-length λ; the number of waves per second is the frequency ν, which is given in Hertz (Hz) (1 Hz = one oscillation per second). The speed v of propagation of the wave is a measure of the number of wave-lengths passing a given point per second. It is obviously given by the product of frequency and wave-length: $v = \nu\lambda$.

Oscillations of this kind with a frequency of about 20 Hz up to about 16–20,000 Hz are perceived by the human ear as sound. We can nowadays produce frequencies well above the limit of audibility (up to 5.10^8 Hz or 500,000,000 vibrations per sec) and these are known as ultrasonics. These ultrasonic frequencies are produced by means of a piezo-electric oscillator in which (by using the *piezo-electric effect*) electrical oscillations of high frequency bring about intense mechanical oscillations. Ultrasonics can be used to particularly good advantage whenever we wish, by to-and-fro motions or by changes in pressure, to obtain effects such as the very fine fusion of components in alloys or emulsions, the degasification of fluids (for instance, in metal smelting), the forcing of materials through membranes (for instance, medicaments through the skin), for special testing of materials and so on.

The free propagation of waves through space is a comparatively simple affair. What happens, however, when two or more wave-motions over-lap, in other words, when we no longer deal with a simple wave, but with interference of simple waves? The resultant state of oscillation obviously depends on whether these different waves either reinforce or cancel each other. When the effects of two waves at a point can be added, the oscillations at this point will be intensified, otherwise the resulting oscillation will be very weak; and if the effects are exactly opposite, the vibration will vanish (Fig. 2). These "interference effects" are characteristic of all

wave phenomena and can be used to advantage for demonstrating the latter.

A simple method for determining and measuring ultrasonic waves, which of course cannot be perceived by the ear, consists of letting a wave interfere with its own reflection from a wall, thus producing "standing waves" (Figs. 3–5). (This is a general method for demonstrating all types of wave motion.) Regions of smaller or greater compression are formed, corresponding to regions of maximum movement of the air particles ("anti-nodes") and to regions where there is no movement of the air ("nodes"). Lycopodium powder or some other fine dust, or even drops of liquid can be used to demonstrate the movement of air in the "Kundt's dust-tube". In this way we can measure the distance between nodes and anti-nodes, and this is equal to half the wave-length of the original sound wave.

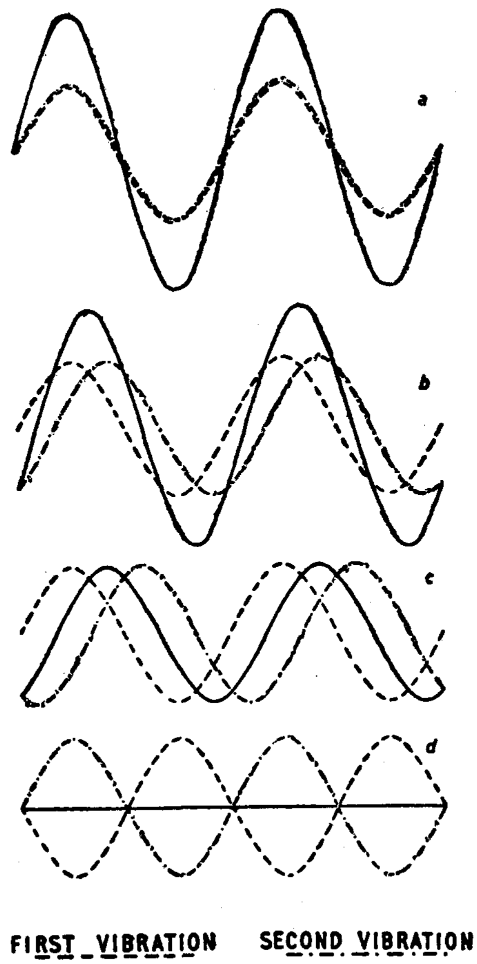


FIG. 2. Composition of two vibrations of equal period and amplitude, but of different phases. (*a*) Reinforcement of amplitudes. (*d*) Cancellation.

The various wave phenomena can be most clearly demonstrated with water waves. The profile of the water wave can be compared to the distribution of the air pressure in sound waves. We shall study in greater detail what happens to water waves when they meet an obstacle. Here we shall make a strange discovery (*see* Plate I): if an extended front of water waves meets an obstacle as, for instance, a plank with a slit not wider than the wave-length, there appears behind the plank a wave phenomenon which entirely corresponds to that which would be created if we had thrown a stone just where the slit itself is located: the water waves spread in concentric circles

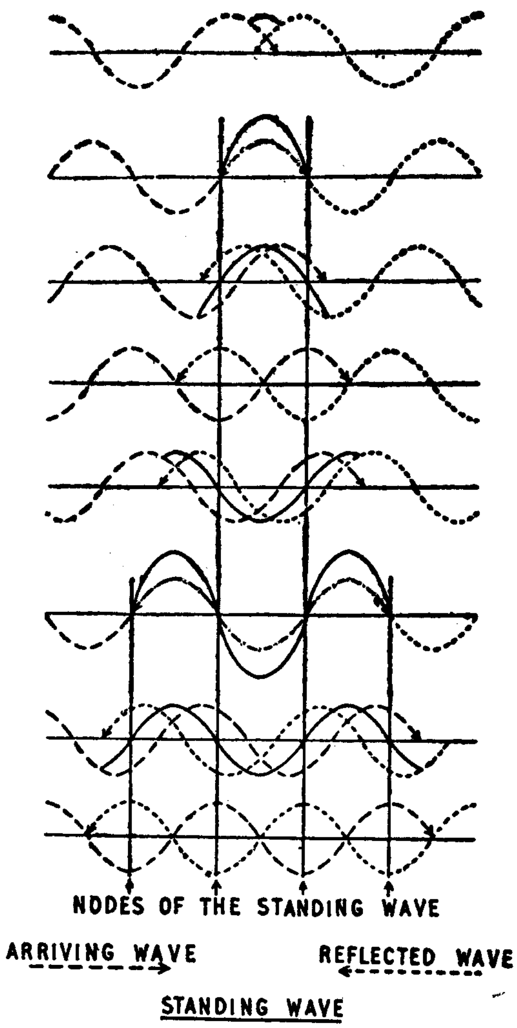


FIG. 3. Origin of standing waves.

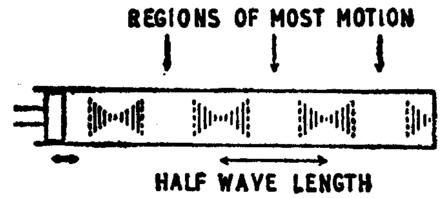


FIG. 4. Kundt's tube with dust figures.

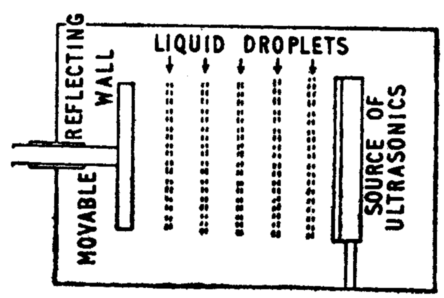


FIG. 5. Ultrasonic standing waves demonstrated by means of droplets.

from that point. If we make the slit a little broader, we shall see a wave band about as large as the slit spreading in the direction of the original wave-motion; but besides it, in certain directions on either side of the band, there are waves of smaller amplitude. With further increase of the size of slit, the band becomes correspondingly broader, the direction of the side waves no longer makes such great angles with the direction of the main band, and the edges of the band become sharper.

These phenomena—and indeed also the free propagation of waves—can be explained by assuming that every particle hit by a wave itself becomes the origin of a new wave, spreading equally in all directions; the wave actually observed is produced by the interference of all these elementary "Huygens wavelets".

The mathematical analysis of these processes cannot be given here, but perhaps they can be made clearer by an example: let us consider two slits very close to each other from each of which there spread circular waves. In a direction at right angles to the plank, both these waves will always reinforce each other, for here two crests due to both openings travel next to each other with equal speed and in the same direction. In fact, they will unite into a wave of double the amplitude. At any other angle, however, this need not be so. Here one wave will precede the other by just a little, and it could happen that at a trough of the first wave there happens to be a crest of the second. Then both waves will cancel each other and there will be no wave at all.

This interference of elementary waves is particularly striking when a wave-front passes through a grating which has regularly spaced and very small openings through which the waves can pass. An elementary wave starts from each opening, and all elementary waves interfere with one another. The resulting picture gives a fan of waves ("diffraction maxima"), whose directions of propagation are dependent on the wave-lengths and the distances of the openings from one another ("lattice-constant"). If the lattice-constant is known, then from the angles made by the diffracted waves, we can obtain their wave-length. This procedure is generally used in the case of light ("lattice spectroscopy").

Audible sound in air has a wave-length of about 20 m for the lowest notes and up to about 2 cm for the highest notes. For the medium tones the wave-length is between 1 and 5 m. Since most everyday obstacles have a size of an equal order of magnitude, we cannot, according to what has been shown above for the case of water waves, use these sound waves for the detection of special directional effects, since in passing round the obstacle the waves are bent, so that sound, e.g. speech, can even be heard around corners. Ultrasonic frequencies however, because of their considerably shorter wave-length—in air down to an order of magnitude of 1/100,000 cm—show good directional effects, and this can be used for the beamed transmission of information by "sound".

A beam of ultrasonic waves can penetrate large distances, especially in water, with little loss of energy. Thus ultra-sound

is used for instance, for echo-sounding, i.e. for determining the depth of the sea by measuring the time that sound takes to travel from a ship to the bottom of the sea and, after reflection, back to the ship again. Bats use a form of echo-sounding with ultrasonics in air to estimate the distances of obstacles in their path. Furthermore, since high-frequency ultra-sound spreads rectilinearly, it is very useful in testing materials. Solid bodies, especially metals, pass sound waves very easily, but this is not the case when there is a lack of homogeneity (cavities, flaws, etc.). Scattering of sound then enables the flaw to be located.

Hydrodynamics

Mechanics can also be applied to the flow of liquids and gases. It is then called hydrodynamics and aero-dynamics and is of the greatest technical importance. The building of ships and aeroplanes, of pipes and flow channels is determined by hydrodynamical considerations. The dynamics of flow is involved in subjects allied to physics as well. Weather is a problem of the flow of air masses. Oceanography is concerned with the flow of the sea. Recently we have begun to deduce the history of the development of stars and star systems from the laws of flow of interstellar gas.

We wish to stress the one phenomenon with which most modern flow theory is concerned, namely turbulence. Experiments show that there are two essentially different forms of flow—laminar and turbulent. In laminar flow, the various parts of the fluid flow regularly next to one another in smooth paths. Thus broth runs from the spoon, asphalt from the drum. In turbulent flow, the single particles of the fluid execute additional irregular movements which are very often vortical. Thus whirls in a flowing river, the irregular quickly-changing appearances of clouds, are common examples of turbulence. The fact that our weather, in which various masses of air fight for supremacy, is so little predictable, is due to the fact that air-flow is turbulent, and the details of the lines of flow cannot therefore be calculated rigorously.

Experiments show that laminar flow is only stable when the fluid or the gas is sufficiently viscous and streams sufficiently slowly in a sufficiently narrow space. The viscosity of a fluid or of a gas is the force which causes neighbouring particles to

stick to each other, and this tends to produce "smooth" motion. If the motion is too violent or too extended in space, a flow which was initially laminar may very often be changed into turbulence by means of small disturbances. According to modern conceptions, turbulence is considered the "natural" form of motion of a not too viscous fluid, on which laminar flow can only be imposed when the field of flow is narrow and the rate small. Why then is turbulence the natural form of motion of fluids? Here, for the first time, we meet statistical consideration.

Turbulence is the most probable form of motion of a fluid, and it is a generic name for numerous, only approximately similar, states of non-laminar flow. We can say a fluid, being a continuous mass has innumerable "degrees of freedom" (*cf.* page 30 ff.). We cannot predict which of them it chooses for its flow in each case, without an exact knowledge of the finest details of the original conditions, and of the forces involved.

Of all the possible states of flow in which the particles can move in very many different ways, there is only one which is absolutely regular: laminar flow. Thus, it is only one out of innumerable degrees of freedom. The contention that the turbulent form of flow is the most natural, means no more than this: if we do not know exactly what original form of flow a fluid would choose, it is most improbable that it should just happen to choose laminar flow. Every other form of flow is turbulent.

This approach can be justified by an exact analysis of the possible solutions of the hydrodynamic equations of motion. Here we cannot enter upon this.

PART II: HEAT

Chapter 5

THE BASIS

THE theory of heat is the best example of the inter-connection of a certain quality of sense impression with purely mechanical concepts. It therefore demonstrates the possibility and the limits of a "mechanical explanation of nature". "Heat" is originally a sense experience. "This soup is warm; that ice is cold." The physicist says: "Heat is a disordered movement of atoms." What is meant by the concept of "heat" in both cases?

Temperature

The sensory impression of "heat" is not a movement of atoms. It does not belong to the subject matter of physics, but to those given facts without which physics would be impossible. It could only be explained by an understanding of the inter-connection between matter and sense impression. In the introduction we said that physics has been based on the renunciation of posing such questions. Now we generally find that when an object is felt to be warm, a whole series of properties can be demonstrated in it which we consider as the causes of the feeling of warmth, without quite knowing how it comes about. The set of these properties, this condition of the warm object, is called "heat" by the physicists. Today we can say that in this sense, heat is a disordered movement of atoms.

The physical theory of heat begins with an objective measurement of heat, with thermometry. Heat is, as experiments show, mostly connected with the expansion of bodies. The mercury in the thermometer is the higher, the hotter it is. In other words, the length of the mercury thread, a geometrical magnitude, is now made the measure of heat. Heat so measured is called temperature.

The scale, on which we measure temperature is quite arbitrary. Today we usually employ the Centigrade scale, on

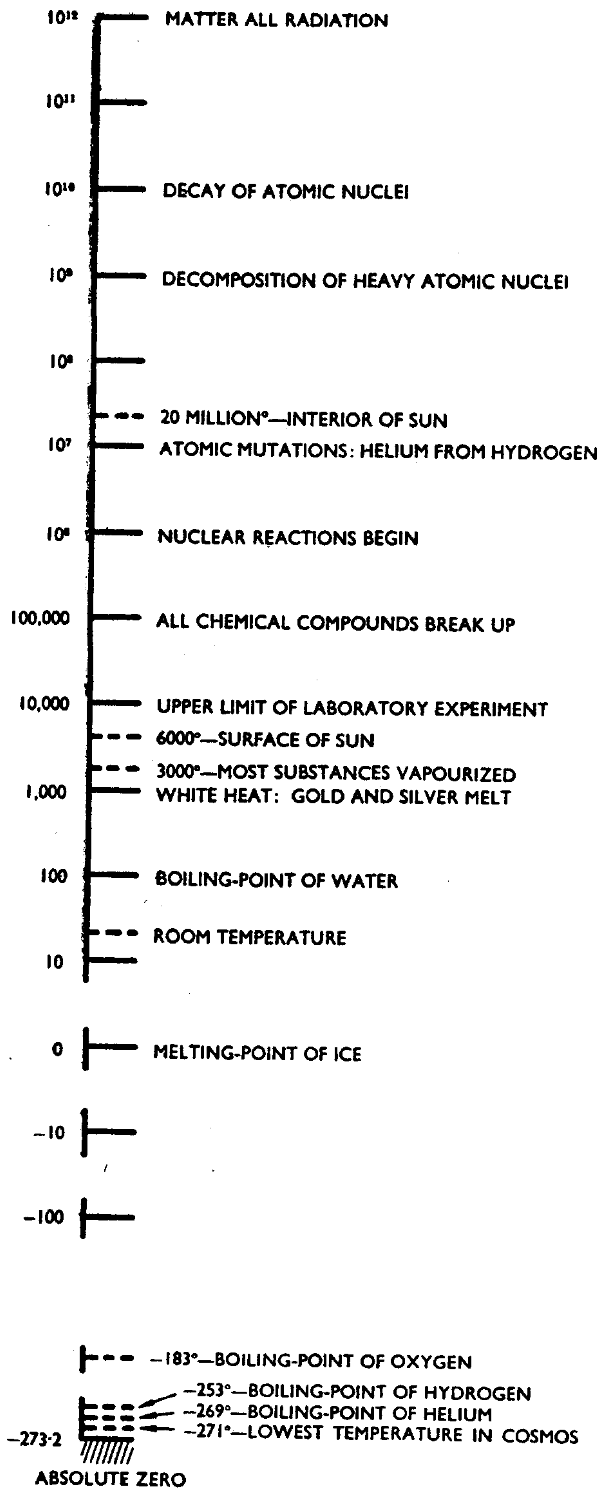


Table I: Temperature Scale

which the height of the thermometer at the melting point of ice is called 0° and that at the boiling point of water 100°. If instead of mercury, another substance were chosen, and its expansion were measured, the sub-divisions on both thermometers would not correspond if, as suffices for practical purposes, they were simply represented by a linear subdivision of the scale between 0° and 100°; different materials expand differently with heat.

The temperature scale only becomes unequivocal if we choose a universal thermometer substance. For this, the ideal gas is chosen. This, as its very name implies, is a simple idealisation. All gases, provided they are heated sufficiently above the temperature at which they are liquid, obey to a good approximation a very simple law which is called after Boyle, Mariotte and Gay-Lussac and which may be formulated as the "ideal gas equation". If we keep the temperature of a gas constant, we can alter two quantities for a given mass of gas: the pressure (p) which is exerted on it, and the volume (v) which it occupies. According to this law, volume is inversely proportional to pressure, or in other words, the product of pressure and volume is a constant ($pv = const.$). By the exertion of great pressure the gas can be compressed to a small volume, and under small pressures it assumes very large volumes; if the pressure were completely removed, it would expand infinitely.

Now, if we alter the temperature (T), the product of pressure and volume can be shown to be proportional to the temperature ($pv = \mathfrak{R}T$—in which equation temperature must be measured in °K [*see* below]). If we raise the temperature of a gas at constant pressure, its volume increases; it is for this reason, for instance, that the air in the atmosphere becomes thinner when it is heated. If, however, a gas is heated in a vessel of fixed volume, the pressure which it exerts on the walls increases. It is this pressure which is applied in an engine for driving the piston.

In the gas thermometer we measure the volume of a gas at constant pressure, and thus determine its temperature. The gas equation here leads to one of the strangest consequences: to the existence of an absolute zero point of temperature. We know that at a fixed pressure, temperature is proportional to the

volume of gas. This volume cannot become smaller than zero, thus temperature can never be smaller than the value which corresponds to the volume zero, which is also known as "zero temperature". It is 273·2° below the zero point of the Centigrade scale. The temperature measured from the absolute zero point is distinguished from 0°C (Centigrade) by being called °K (Kelvin degrees). It is possible that the temperature in space outside the spiral nebulae differs by only a fraction of a degree from absolute zero. In our laboratories we have approached this zero point within some thousandths of a degree. According to a certain law (the theorem of Nernst) it can never be fully reached.

It must be remarked that no real gas obeys the ideal gas equation down to the absolute zero point. All gases deviate from it with increased cooling, and finally become liquid, the last to do so being helium at 4°K. Thus the existence of an absolute zero point can only be derived hypothetically from the ideal gas equation. The further development of thermodynamics has confirmed its existence; in the kinetic theory of gases we shall meet a simple interpretation.

Energy

Apart from temperature we must introduce a second measure of heat, the quantity of heat. A litre of water at 99°C contains a certain quantity of heat. Two litres of water at 99°C, although they have the same temperature, obviously have twice the quantity of heat as one litre at 99°C, and could obviously do twice the amount of work on evaporation.

Here we come face to face with the interconnection between the quantity of heat and work. Heat can be changed into work and vice versa. R. Mayer and Joule established the work equivalent of a given quantity of heat, and from this the general law of the conservation of energy, which is also considered the first law of thermodynamics.

As we saw, the energy law of mechanics is only valid under limiting conditions. Mechanical energy can be destroyed through friction. However, through friction, heat is created. Robert Mayer was the first to realise that this quantity of heat, if measured correctly, would be identical with the lost mechanical energy: heat is a form of energy.

The general law of energy states that energy can neither be created nor destroyed, but that only its manifestations can change. Apart from mechanical and thermal energy there are yet other forms: electrical, magnetic, chemical, and the now famous energy of the atomic nucleus.

We may well ask what makes us so certain about so general a law. Mayer obtained it from what to us must appear as an unconvincing philosophical consideration, connected with the statement "*causa aequat effectum*" (the cause is equal to the effect); he thus brought together the law of energy and the so-called causal law. Energy, however, in so far as it is clearly definable only in terms of the law of conservation, is a substance rather than a causal concept. Helmholtz, starting from ideas of the point mechanics of atoms, considered heat energy as the kinetic, and chemical energy as the potential energy of the atoms, and thus referred back the general law of energy to the special law of energy of mechanics. Today we know that the law of energy is equally valid both in atomic and in field physics, although these are very far removed from classical point mechanics. The law of the conservation of energy has shown itself to be a more fundamental concept than classical mechanics.

The law of the conservation of energy can also be called the law of the impossibility of perpetual motion. A *perpetuum mobile* would be a machine that could perform continuous work without any other lasting changes in its internal or external condition. A "perpetuum mobile in reverse" would correspondingly absorb work constantly without any reciprocal action. Both contradict the law of the conservation of energy. It is this negative formulation which demonstrates clearly the boldness of every general statement of the type of the energy law: it could be refuted by the construction of a single contrary example, through the construction of a single perpetuum mobile. These laws, however, are indeed valid, for hitherto no contrary example has been produced.

The depth of our faith in natural laws becomes most apparent when we ask what would happen if somebody did produce a perpetuum mobile. We should look for the conditions under which it works, and by stating them, we would limit the law of conservation of energy to a domain of validity. In

this case, the general natural law would be: "... in cases A, B, C ... energy is conserved, in cases D, E, F ... it is not in the following way. . . ."

Entropy

All processes that take place around us and in us are, strictly speaking, irreversible. True time cannot, like a film, be run backwards. The laws of mechanics do not express this irreversibility. For instance, the exact reversal of the motion of a planet or of an undamped vibration is, according to mechanics, again a possible motion of the planet or a possible vibration. Neither does any true law of conservation, such as the law of the conservation of energy, involve a direction in time. It has been shown that even the basic laws of the electro-magnetic field and of atomic physics do not involve irreversibility of time. This property of true, historical time is expressed only in one place in contemporary physics—in the second law of thermodynamics.

If we pour cold water into hot, both temperatures become equal, without any work being done. This process cannot be reversed in any way without expending some external energy, or without making some changes in the environment which, in their turn, are irreversible. A body in motion can be brought to rest through friction. If, however a body at rest is warmed with the heat thus liberated, this does not immediately put it into motion. We can say that although work can generally be completely changed into heat, heat cannot be completely changed into work. Differences of temperature may be used for doing work; as is done for instance, in the steam engine. However, the quantity of heat found at the lowest working temperature cannot be changed into work. Otherwise we could build a machine that gains energy, by simply cooling the ocean. This second law can be formulated as the law of the impossibility of a "perpetuum mobile of the second kind", i.e. of an apparatus which does work simply through cooling a heat reservoir, without anything else permanently changing in the world.

The mathematical formulation of this law leads to the definition of a new magnitude, *entropy* (Greek—"turned within"), which may be taken as a measure of the energy

lost in the form of heat and not available for work. The existence of irreversible processes is expressed in the fact that the entropy of a system isolated from its environment can only remain constant or increase during any physical processes within this system, and that it can never decrease. A process in which the entropy remains constant is reversible, one in which it increases is not. Very strictly speaking, there is no process in the world which is reversible, for there is always a slight increase in entropy.

Chapter 6

THE CONNECTIONS BETWEEN HEAT AND ATOMISM

WHAT we have considered up to now is "phenomenological thermodynamics". In it are derived the connections between pressure, volume, temperature, energy, entropy, etc., without trying to refer the phenomenon of heat itself to other (e.g. mechanical) processes. Many facts, however, become much clearer if we assume that heat is a disordered motion of atoms.

The Kinetic Theory of Gases

At first this leads to a simple interpretation of aggregate states. In the solid state, the atoms are held in fixed positions by their mutual forces; it is for this reason that the body as a whole retains its shape. In the fluid state, the thermal motion of the atoms is greater. It is true that the forces still keep them attached to one another, but they move past each other much as do people in a crowd; and thus liquids can take on any shape. In a gas the atoms are spread far apart or, at best, they remain united in smaller groups, the molecules. Every gas molecule flies freely through space until it meets another molecule or a wall of the container. Here it is strongly deflected for an instant, and then again follows its inertial path until the next collision.

This model explains the gas equations. Temperature is a measure of the kinetic energy of each molecule. The pressure which the gas exerts on the wall is due to the continuous collisions of the molecules with the wall. Each square centimetre of the wall at room temperature and at normal atmospheric pressure is hit by approximately 2.10^{23} molecules per second, each of which although it only weighs 5.10^{-23} gm nevertheless collides with an average velocity of half a kilometre per second. If, at constant volume, we increase the temperature, both the number of collisions, and also the change of momentum at each single collision, will always be increased proportionately to the average velocity of each molecule; the pressure exerted therefore, is proportional to the square of the velocity, i.e. to the

kinetic energy, and thus to temperature. If we enclose one and the same mass of gas at the same temperature, first into a volume of one litre, and then into two litres, then because of the greater density twice as many molecules will hit the wall in the first case and therefore the pressure will be doubled.

The absolute zero point is now shown to be the limiting temperature at which molecules will have no movement. It will be obvious that the concept of further cooling is nonsense; there is no lesser motion than rest itself. But it will also be obvious that matter when it approximates this condition, will cease to be gaseous. The atoms will then hardly move at all and will only occupy a small space, touch one another, stick to one another, and form a liquid or a solid.

The kinetic theory of gases (Greek: κινησις =movement) can further explain conduction of heat, diffusion and the viscosity of gases. It tells us not only the average energy of the molecules but also how the velocities of the molecules deviate from the mean (Maxwell's velocity distribution). The kinetic interpretation of the second law (Boltzmann's H-theorem) is better discussed independently of the special case of the ideal gas.

General Statistics

In the kinetic theory of gases temperature is a measure of the average energy of the molecules. The energy of every single molecule can never be known to us, since two grams of hydrogen (at atmospheric pressure and at a temperature of O°C in 22·4 litres) contains 6.10^{23} molecules (Loschmidt's or Avogadro's number). The kinetic theory of gases is therefore essentially a statistical theory. With it, probability has become an important concept in physics.

The statistical character of the theory rests not only on the great number of molecules, but also on the fact that heat is a disordered motion of molecules. Let us remember what we said above (pages 40–41) about the concept of disorder in dealing with turbulence. Historically, the concepts discussed there were first used in the kinetic theory of gases and in the general statistical theory of heat, and only in the last fifteen years have they been applied to turbulence (by G. I. Taylor and others). Here we shall take up these ideas in a form suited to the theory of heat.

"Disordered motion" is a generic name for many different forms of motion, the differences of which we cannot or do not want to investigate for each single case. In a given mass of gas only the thermo-dynamic magnitudes of its states such as pressure, volume, temperature, quantity of heat can be easily observed. The latter, however, characterise the condition of the molecules only very summarily. Let us consider two equal volumes of gas at equal pressure and at equal temperature. In the two cases the two sets of individual molecules can easily execute quite different motions. Thus two gases seen macroscopically (i.e. observed with the usual large scale laboratory equipment) can be in the same condition; we say that they are in the same macro-state (μακρος=great). Equally, "microscopic" observation of all molecular movements would reveal quite different micro-states, which agree only in the average energy of the molecules and some similar "macro-magnitudes". If we knew the micro-state, this would naturally also give us the macro-state. Every micro-state, therefore, belongs to a certain macro-state. Conversely, to each macro-state there belong very different possible micro-states.

The usefulness of these concepts is shown in the statistical interpretation of the second law (Boltzmann). It seems paradoxical that a law, which propounds the irreversibility of thermal events in general, should be derived from a theory which refers heat to the motion of atoms and then applies the concepts of mechanics to these motions. On page 50 we observed that neither classical mechanics nor modern atomic mechanics involves the irreversibility of time. For the sake of simplicity, we shall here stick to classical mechanics, which was all that Boltzmann had at his disposal. According to the equations of mechanics, every possible motion of the atoms could take place equally well in the reverse way. Now if heat is motion of atoms, why then should not each thermal process be able to run in reverse? It seems as though the kinetic interpretation of heat contradicted the second law directly.

In reality, irreversibility is not introduced into the kinetic theory of heat by mechanics, but by statistics. The concept of probability contains a reference to the direction of time which, it is true, is only introduced into the usual representation of this theory in a very veiled manner. We may emphasise this by

saying that: probability is a quantitative interpretation (and a narrowing) of the concept of possibility. "It is possible that with the next throw of this die we shall throw a six." This is a relevant statement, but it can be made more precise as follows: A six will fall with the probability 1/6. Statements of probability about actual events, just like other predictions derived from natural laws, can be tested empirically. Ex hypothesi, however, they cannot be tested in a unique case, but only in an aggregate of cases, a "collective". A statement of probability is empirically tested as a statement about relative frequencies: "How often amongst a sequence of many throws do we throw a six?"

What connection has this concept with the direction of time? Only future events are possible. They alone have the uncertainty which gives meaning to questions about the probability of their happening. Past events are facts. To ask about the probability of their occurrence is senseless, for they are already realised. Already fifty years ago, the philosopher Bergson had stressed this basic difference between the open, uncertain future and the performed past as distinguishing the structure of real time (*durée réelle*) from the physicists' formal spatial concept of time. This is rather ironical for, not clearly understood by physicists and outside the paths of philosophers, it was just this time structure which was used in the statistical derivation of the second law.

In detail the usual argument runs as follows: let a physical system be in any macro-state whatever. We ask in what macro-state it will be a little while later. To predict this exactly we should really know its micro-states. These, however, are unknown. Therefore, we can only ask with what probability the system will pass into one or another state. Now, macro-states differ as to micro-states contained in them. For instance, let us compare two bodies in which the total kinetic energy of the molecules is the same. Let one be cooled to absolute zero and let its entire kinetic energy be used to set the body as a whole moving through space at great speed. Let the other be considered as a whole body at rest, and let the kinetic energy of its molecules be in the form of a disordered to-and-fro motion, i.e. of heat. Both are well-defined macro-states. In the first case the micro-state is completely determined by the macro-state; every molecule has the same velocity (both in

magnitude and direction) as the centre of gravity of the whole body. In the second case, there are possible innumerable forms of motion of the individual molecules; this macro-state comprises very many different micro-states.

Now the micro-state of a body will develop on the basis of the physical processes going on in it and of the interaction with neighbouring systems, but we do not know the details of how this will happen. After some considerable time has passed, the body will be in some other micro-state. If we do not know anything else but this, it is, nevertheless, obviously more probable that this micro-state will belong to a macro-state which comprises many micro-states, rather than that it should be "snatched" into a macro-state corresponding to only a few micro-states, let alone one. In the case of the fast-moving body at absolute zero mentioned above, the body may for instance, redistribute its total energy to its molecules through some kind of interaction. It is extremely improbable that, after such an interaction, its molecules will still all be moving parallel to each other. It is much more probable that the body will be in one of the many micro-states classified under the heading of "disordered internal movements", i.e. most probably its kinetic energy of macro-movement is changed into heat. If, on the other hand, we consider the warm body at rest in the second case mentioned above, and if we let its molecules exchange energy, it is most probable that the molecules will still be moving in a disordered way. It is most improbable that order is created out of disorder "by itself", i.e. that macro-molecular energy is created from heat.

The improbable occasionally happens. We know of "fluctuations" in which heat visibly produces movement. An example is the Brownian movement of small particles suspended in air or in water, which can be observed in the microscope: an irregular, aimless to-and-fro movement which becomes the livelier the smaller the particles are. This movement is due to the fact that these dust particles are being continually struck by the even smaller molecules, now from the one, now from the opposite side. However, to see a stone jump up from the ground due to a sudden cooling, we should have to wait a time greater than the age of the earth. In this case, such a very great improbability is a practical impossibility.

PART III: ELECTRICITY, MAGNETISM AND LIGHT

Chapter 7

THE ELECTRO-MAGNETIC FIELD

SOUND and heat can be derived from motion and since the seventeenth century there have also been mechanical theories of light. Newton assumed that light rays were the trajectories of small material particles. Huygens considered light as a vibration comparable to that of sound. Young and Fresnel showed, through their interference experiments, that light did in fact have the nature of a wave. It was known that the spectral decomposition of white light into colours, discovered by Newton, is the equivalent of a division into wave-lengths: the difference in colour is simply an immediate sense experience of what we call the difference in wave-lengths of different vibrations.

The Problem of Light

What is it that vibrates when we see light? It is not the air or any other known material medium. Light can pass both through evacuated glass tubes, and through interstellar space dividing us from the sun and the distant stars, without being impeded. A very thin, all-pervading body capable of vibrating —the ether—was postulated as an attempted explanation. Lord Kelvin confessed that the ether was nothing but the subject of the verb "undulate". The assumed mechanical properties of the ether (greatest possible rigidity because of the quick propagation of light, and at the same time, lowest possible density because it has no observable mechanical manifestations) were paradoxical.

In the meantime, other manifestations of this unknown something, called the ether, had been observed for quite some time, but their connection with light was still unknown: electrical and magnetic effects. At the turn of the eighteenth century, these had become the object of great discoveries and much speculation. They were the first examples of an unquestionable physical reality, which could neither be perceived

by our senses, nor imagined simply by means of "material" pictures. Light, sound, heat are immediate sense data. Electricity and magnetism were first deduced from the ability of certain bodies to move other bodies. Only the mechanical concept of force allowed us to give a quantitative description of electricity and magnetism as the causes of these measurable movements. Faraday discovered that it was not in the bodies which were known as carriers of electricity and magnetism, but in the space between them—the electro-magnetic field—that the decisive processes took place. Maxwell derived the theoretical result, that this field ought to be capable of sustaining wave-like vibrations, and Hertz discovered these vibrations experimentally. Radio and radar are the technical consequences of this discovery.

Now, there were two kinds of unexplained waves—those of light and those of electro-magnetism. Was there an "electro-magnetic ether" as well? What was the physical reality of Faraday's field?

Both problems are in fact, only one problem. Maxwell established that electro-magnetic waves must travel with the same velocity as light, and he concluded that light was an electro-magnetic wave motion. Today this theory is confirmed in many ways. A little later on we shall discuss the wave-length scale of electro-magnetic waves in which visible light occupies only a modest octave.

Today the laws for the field quantities are known in the form of Maxwell's equations of the electro-magnetic field. All the many endeavours to find mechanical models which would give such laws of motion have been fruitless. Michelson's experiment and its interpretation by Einstein in the special theory of relativity (*see* page 90) show that the "ether" cannot even be assigned a reference system in which it is at rest. The search for mechanical ether models was gradually abandoned.

Today we know, from atomic physics, that the impenetrability and the elasticity of matter are not basic properties, but that they follow from the deeper "quantum mechanical" laws as certain limiting cases. The familiar forms of matter—solid or gaseous—which were taken to serve as models for the ether, are themselves only superficial manifestations.

Inside the atoms electrical forces are at work. Thus we must not reduce electricity to mechanics, but rather mechanics to electricity.

Today the electro-magnetic field, as described by Maxwell's equation, is taken as a fundamental reality of nature whose connection with elementary particles or fields has not yet been explained. That this has not led us to a "mechanical" theory of light (comparable to the theories of sound and heat) is due to the fact that the electro-magnetic field, in contradistinction to the material field, does not produce any separate "bodies", such as atoms. This is a special trait which, as was remarked in the Introduction, is due to the fact that while matter obeys Pauli's Exclusion Principle, the electro-magnetic field does not.

The limitation of the wave concept which is connected with the discovery of light quanta, will be discussed in Chapter 10.

Processes in the Electro-magnetic Field

The term electro-magnetism covers two groups of phenomena, whose connection was only discovered in the beginning of the nineteenth century: electricity, discovered by the effects of amber (Greek: ηλεκτρον =amber) and cat's fur, of which the most impressive manifestation was lightning; and magnetism, originally known as a property of iron and magnetite. These phenomena remain separate, as long as static processes unchanging in time are considered; but even in static cases they have very similar properties.

Electricity and magnetism both appear in two related polar forms. We differentiate between "positive" and "negative" electricity, "north" and "south" magnetism. However, while the two forms of electricity can be separated from each other, those of magnetism cannot. One body can have a positive, another a negative charge, while a piece of iron, for instance, can only be polarised magnetically so that one of its ends contains a north pole and the other a south pole. The first demonstration of electrical charges was made possible through the force that charged bodies exert on one another according to the law: equal charges repel, unequal charges attract each other. Exactly the same law is valid for magnetic poles.

The correspondence of the laws goes even further. A very narrowly concentrated charge in space exerts on another equally concentrated charge a force that is inversely proportional to the square of the distance (Coulomb's law). Exactly the same law applies to the magnetic pole. It must be stressed that the mathematical form of the law is exactly the same as that of Newton's law of gravitation. Today we are of the opinion that this agreement is no accident. To gravitation, electricity, and magnetism alike there apply simple basically similar field equations, and it is for this reason that they have similar solutions. Probably no other forms of equation are possible for the elementary fields and, although we do not understand it fully, the reason may well be connected with the foundations of geometry (the theorem of Pythagoras).

When charges move we have an electric current. Galvani and Volta found a continuous source of current in chemical processes taking place in solutions. Today we know that during electrolysis, electrically charged particles of the atoms separate from each other and travel towards the opposite terminals—the electrodes. The quantities characterising a current are related by Ohm's law: the current is equal to the potential divided by the resistance.

The current is that quantity of charge which flows through the conductor in unit time. The expression current is reminiscent of water currents. The strength of the current then corresponds to the rate of streaming of the water. The potential in this comparison corresponds to the pressure gradient of the water flow. The simile is exact. The charge moves because an electrical force is acting on it. Force times distance equals the work done, which in this case is precisely the product of the quantity of charge conveyed and the potential. In a metal wire it is the electrons, which we shall consider more fully when discussing atomic physics, that are the carriers of the current. The strength of the current is then proportional to the number of electrons moving through the conductor per unit time. The resistance can equally be understood as the frictional resistance which the electrons experience in rushing through the metal built up of atoms. As in every other case of friction, heat is created (Joule's law). The law of the conservation of energy can also be proved in the case of electricity.

Oersted discovered that every electric current is surrounded by a magnetic field. Ampère found that a magnetic field exerts a force on an electric current. This could have been expected from Oersted's discovery, since the current causing the magnetic field acts just like a pair of magnetic poles (a solenoid, for instance, acts like a rod magnet), and we know that magnetic fields exert forces on magnetic poles. On the other hand, an entirely new phenomenon was discovered by Faraday, namely induction: a change of magnetic field in the vicinity of an electrical conductor produces a current in the latter. A moving magnetic field corresponds to an electromotive force. This is a symmetrical completion of Oersted's discovery, according to which a moving electric charge creates magnetic forces.

Field and Action at a Distance

In our previous considerations we often had to use the concept of "field". We must now define it a little more precisely. Let us think of a charge concentrated in space (point charge). It exerts on another point charge (the test body) brought into its vicinity, a force which depends, according to Coulomb's law, on the distance between both charges. Thus, the process could theoretically be ascribed to effects at a distance. But equally well we could say that the charge changes the condition of space in its vicinity, and that the force on the test body is just the way in which this change manifests itself. This force is taken to be equal to the product of the charge of the test body and the electrical field strength, at any place on the test body. Coulomb's law then states that in the neighbourhood of a point charge the electrical field strength is inversely proportional to the square of the distance from it. Thus read, it is a law of field physics. Magnetic field strength is defined in an analogous manner.

The difference between the theories of actions at a distance and of fields is so far only a difference in modes of expression. A factual difference appears only in the case where the field is changing in time. If a charge is moved, the question arises as to whether the whole field follows this motion instantaneously, i.e., whether it is rigidly fixed to the charge, or whether changes in the field can only be propagated with a finite

velocity. This difference can be conceived as a difference in our ideas as to the causality prevailing in the field. According to the first hypothesis, the strength of the field at every place is an immediate effect of the charge producing it ("action at a distance"). According to the second assumption, the field exerts effects on the field at neighbouring or contiguous points; field-changes are not only effects, but also causes. If all field-changes spread only in this manner, we speak of a consistent "contact-action theory."

Faraday and Maxwell built up a theory satisfying contiguity. The fact that field-changes appear as the causes of other field-changes is especially noted in Maxwell's concept of the "displacement current". The strength of the magnetic field produced by a current is given by the Biot-Savart law in which a closed circuit is considered as a magnetic "double layer" [a pair of north and south poles spread over planes placed immediately next to each other, whose (dipole) strength depends on the strength of the current and the area circumscribed by the current]. This is proved by experiment. But what happens if the circuit is not completely closed; for instance, if two plates facing each other (condenser) have been given charges of opposite sign and if they are discharged by means of a wire loop?

Maxwell noticed that although no charges travel in the open part of the circuit between the plates, something physical takes place: during the discharge of the condensers, the electrical field becomes reduced. Maxwell considered this change of field as equivalent to a current, calling it a "displacement current", and he assumed that, like any other current, it produces a magnetic field. Only in this way can symmetry with Faraday's law of induction be established, for since a magnetic pole current does not even exist, it is only the change of the magnetic field in the neighbourhood of the conductor which can be responsible for the origin of the electromotive force or, in other words, the electric field strength.

Experiment has confirmed Maxwell's hypothesis. The latter leads to the electro-magnetic wave being considered

as a process in which changes in field are propagated through space alternately as effect and as cause.

Waves in the Field

Let us consider an electro-magnetic analogy of mechanical vibration—the so-called oscillatory circuit. Let us apply electric charges of opposite sign to the two plates of a condenser so that there is a given potential difference between them. If we connect the plates by means of a conductor, for instance a coil of wire, then the charge will flow through the conductor in the form of a current. According to Oersted this builds up magnetic fields in the neighbourhood of the conductor. According to Faraday this field, since it is changing and not constant in time—it appears and disappears—induces an electrical potential in the conductor itself. This process is called self-induction. This potential is opposite to the original potential of the condenser. After having first been discharged by means of the current, the condenser is now recharged in the opposite sense by this induction. The process is then repeated in the reverse direction and so on; this is fully analogous to mechanical vibrations: to the state of maximum potential energy—the maximum displacement of a pendulum—there corresponds the state of the greatest discharge of the condenser; to the maximum speed (maximum kinetic energy) of the pendulum when traversing the position of rest, there corresponds the

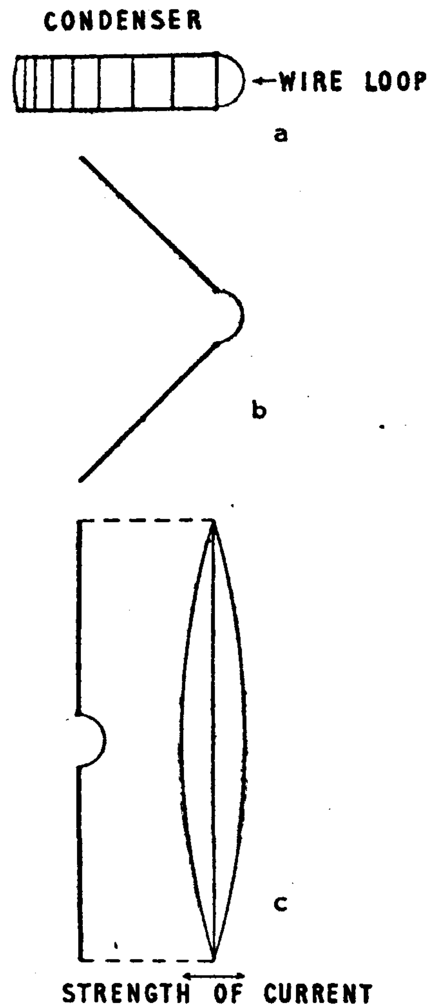


FIG. 6. (*a*) Closed oscillatory circuit consisting of a condenser and a semi-circular self-inductance. The density of the field lines, which give the direction of the force acting at each point, is a measure of the field strength. (*b*) *and* (*c*) Opened-up condenser plates. (*c*) Dipole oscillatory circuit and distribution of current strength in the dipole.

maximum value of the current at that point in time, in which the condenser changes from one polarity to the other. Just as a mechanical vibration is damped by friction, so the electromagnetic energy is used up by the electrical resistance of the oscillatory circuit (for as we have seen, electrical resistance can be considered as the frictional resistance of the electrons in the conductor): "a damped electrical vibration" is produced.

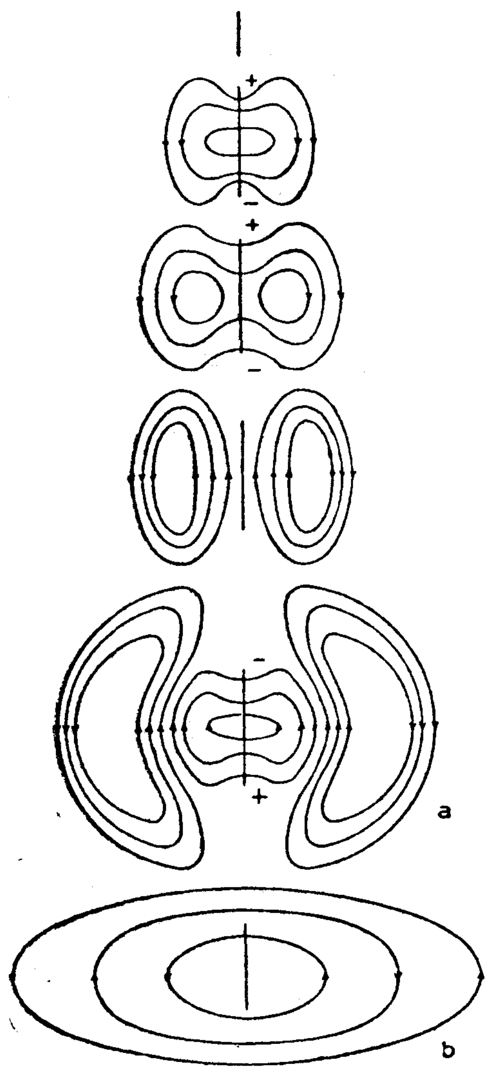


FIG. 7. The electro-magnetic wave in various phases; the spreading of the lines of force from the dipole. (*a*) Electrical, (*b*) magnetic, lines of force.

A collapse of the electric field in the condenser is retarded by self-induction in the conductor; at first the current increases against the self-induced counter potential. With large self-induction, therefore, the charge decays very slowly. As a result the charge on the condenser plates can distribute itself equally at every moment. Although the charge is led away by the conducting wire only at one single point of each plate, the remaining charge has sufficient time to distribute itself evenly on the rest of the plate. Thus, in practice, the same field strength prevails at all points of the condenser. If, however, the self-induction of the conductor is very small, the electric field of the condenser collapses very rapidly. The charges no longer have time to balance one another, and the field strength at different points of the condenser will be noticeably different. In this case, the electric field will travel with a very high, but finite, velocity along the condenser. A field travelling in this way is a displacement current in Maxwell's sense, and thus produces a similarly moving magnetic field in its neighbourhood. The

magnetic field on its part, induces a moving electric field in its neighbourhood. Thus, the oscillation of current and field in the condenser produces a series of oscillating fields in neighbouring space. These can spread from the oscillatory circuit into space just as sound waves produced by a vibrating membrane spread through the neighbouring air. However, the radiation of electro-magnetic waves in the closed oscillatory circuit, which we have considered so far, is very small. It is large in the case of a dipole.

By an electric dipole we generally mean two equal and opposite electric charges a certain distance apart. We produce a dipole by means of two wire halves whose free ends project into space. These two wire halves may be considered as being two unfolded condenser plates. The wire halves, just like the condenser plates in the closed oscillatory circuit, are alternately given positive and negative charges, and the current, the amplitude of which is greatest midway between the two dipole halves, can be demonstrated, for instance by the glow of a little lamp. The distribution of the current, which in the dipole looks like a standing wave, is given by the distribution of the electric field of the dipole which changes quickly with time, closing the circuit in the form of a displacement current around the dipole. Measurement of the velocity of propagation of the electric field—in the laboratory this is most easily done by determining the frequency and measuring the wave-length of a dipole whose two wire halves point in the same way and parallel to each other—shows that the velocity of propagation is equal to that of light. In the Lecher system the waves propagated between the parallel wires spread freely into space. To every change of electric field strength in any part of space, there again corresponds a given magnetic field, determined both in magnitude and direction by Maxwell's hypotheses, and again to every change of magnetic field there corresponds an electric field. The picture created by the superposition (interference) of all these fields in space is best represented by diagrams of the lines of force of the electric field strengths, as introduced by Hertz. It is clear from this that the greatest part of the energy is radiated at right angles to the dipole; no radiation takes place in the direction of the dipole. (*See* Figs. 6–9).

Light waves differ from the electro-magnetic waves pro-

duced in the wire dipole only in that they have a very much shorter wave-length, or in other words, a far greater frequency. The complete electro-magnetic spectrum comprises radio, infra-red, light, ultra-violet and X-ray waves; even the radio-active γ-rays and the energy-rich photons from cosmic radiation to which we shall refer later, belong to the domain of electro-magnetic waves (Table II).

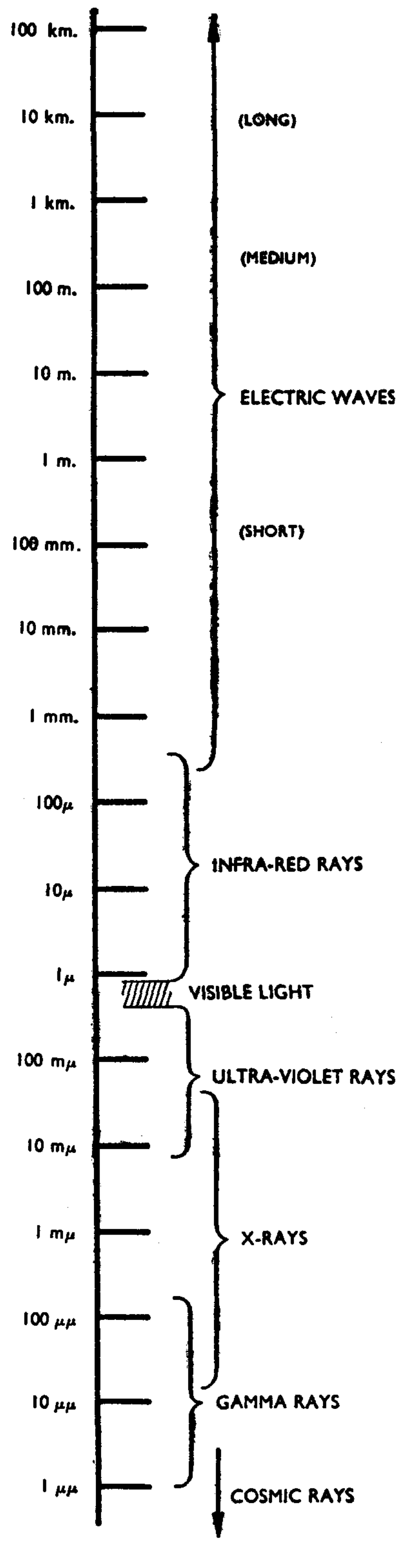


TABLE II: Scale of wave-lengths.

Transition to Geometrical Optics

Geometrical optics uses an older, phenomenological approach: a "light ray" is compared with the undisturbed rectilinear motion of a material particle in space, as in mechanics. This method is indispensable, even today, a as first approximation in calculations concerning optical instruments. It is justified in view of the small wave-length of visible light. As we have already explained in the case of sound, waves are propagated rectilinearly if their wave-lengths are very much smaller than the obstacles which stand in their way. The "ray" is then the direction of propagation of the waves; it is a straight line perpendicular to the wave front. The wave-lengths of visible light lie between 8.10^{-5} cm for red light, and 4.10^{-5} cm for blue light, and are thus very small indeed compared with the dimensions of optical instruments.

Geometrical optics assumes that the angle of aperture of a light wave (conical wave) emerging from a point light source can be made as

small as desired by means of an eye-piece, without disturbing the process of propagation, until we have a "ray" which, in a homogeneous medium, is rectilinear. A wave with a small angle of aperture is thought of as composed of an infinite number of rays which are completely independent of one another. In geometrical optics it is further assumed that the ray could equally well travel in the reverse direction. It is obvious that both the rectilinear propagation and also the independence and the reversibility of light rays neglect the diffraction effects due to the wave nature of light; for what was originally a single light ray would, after diffraction at a very narrow slit (*see* page 37), be split into different rays corresponding to individual diffraction maxima. This process is obviously not reversible. The diffraction effects in optical instruments must therefore, be taken into account in the relevant calculations.

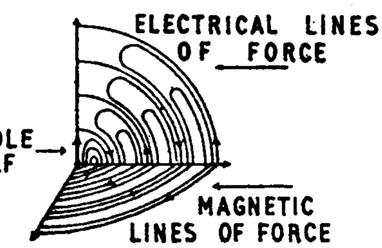


FIG. 8. Instantaneous picture of the electrical and magnetic lines of force of an oscillating dipole (sections parallel and perpendicular to dipole). Hertzian diagram of lines of force.

The propagation of light at the interfaces of different media is governed by the laws of reflection and refraction. In the simple language of geometrical optics, reflection means the bending of the light ray back from the interface into the first medium, and refraction the sudden change of direction at the interface by an amount solely determined by the nature of the media. A deeper cause of refraction and reflection is to be found in the differing velocities of propagation in the two media. Since the frequencies in both media are equal, being determined by the source of light, the wave-lengths of the light are different. Considerations of the continuity of electric and magnetic field strengths lead to the laws of reflection and refraction; an exact consideration of the boundary conditions at the interface gives us the amount of light reflected and refracted and also the directions of vibration of the electric and magnetic field strengths (polarisation relations).

Applications: Radio and Radar

The vibration produced in an oscillatory electrical circuit consisting of a condenser and a wire coil (having self-induction)

would, if it were left to itself, quickly disappear because of damping. The production of undamped electric vibrations required for news transmission and for wireless, is done by means of a relay-like circuit using an electron tube (*see* Fig. 9)—the function of which we shall discuss later (*see* page 78) the condenser always receives the full charge at the right moment. This process corresponds to the fact in mechanics that a pendulum (for instance that of a clock), is restored to its original maximum displacement by a small extra impulse during each vibration. The changes in the self-induced magnetic field produce a current in a second coil connecting the two ends of a stretched wire dipole. This current oscillates with the same frequency (the principle of the transformer; "inductive coupling"). In this way, the oscillations of the closed oscillatory circuit are transmitted to the open dipole circuit—the transmitter which radiates the energy into free space. The field changes spread through space with the velocity of light and can produce in an aerial (dipole) of an oscillatory circuit tuned to the same frequency (resonator) a current oscillating with the same frequency. This is amplified further by a receiver.

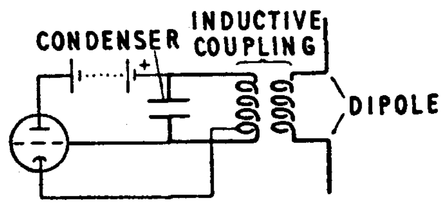


FIG. 9. Inductive coupling of dipole circuit with a closed oscillatory circuit.

Now the electrical oscillatory circuits of radio transmitters give frequencies (10^5–3.10^8 Hz), which are far greater than those which can be perceived by the human ear. They can therefore not serve for the immediate transmission of sound. For this reason, the very high but constant carrier frequency of the oscillatory circuit in the transmitter, must be modulated by the audio-frequency. This can be done by synchronising the amplitude of the carrier frequency with the audio-frequency of which the former is a high multiple (amplitude modulation). By means of suitable circuits, amplitude variations are changed in the receiver into current variations, which are then—for instance in a loud-speaker—changed back into the mechanical vibrations of a membrane, and thus into sound vibrations. It is understandable that amplitude modulation is easily upset by any changes in the field, produced for instance by electric discharges in the atmosphere (lightning), polar light or

sparks of motors; for the discharges, which in themselves are high frequency vibrations, produce strong field changes to which the receiver is sensitive. Sound transmission by frequency modulation is largely free from these disturbances and is used in modern very-high-frequency (VHF) transmission. Here the frequency of the transmitting wave is modulated according to the transmitting tone frequency (*see* Fig. 10).

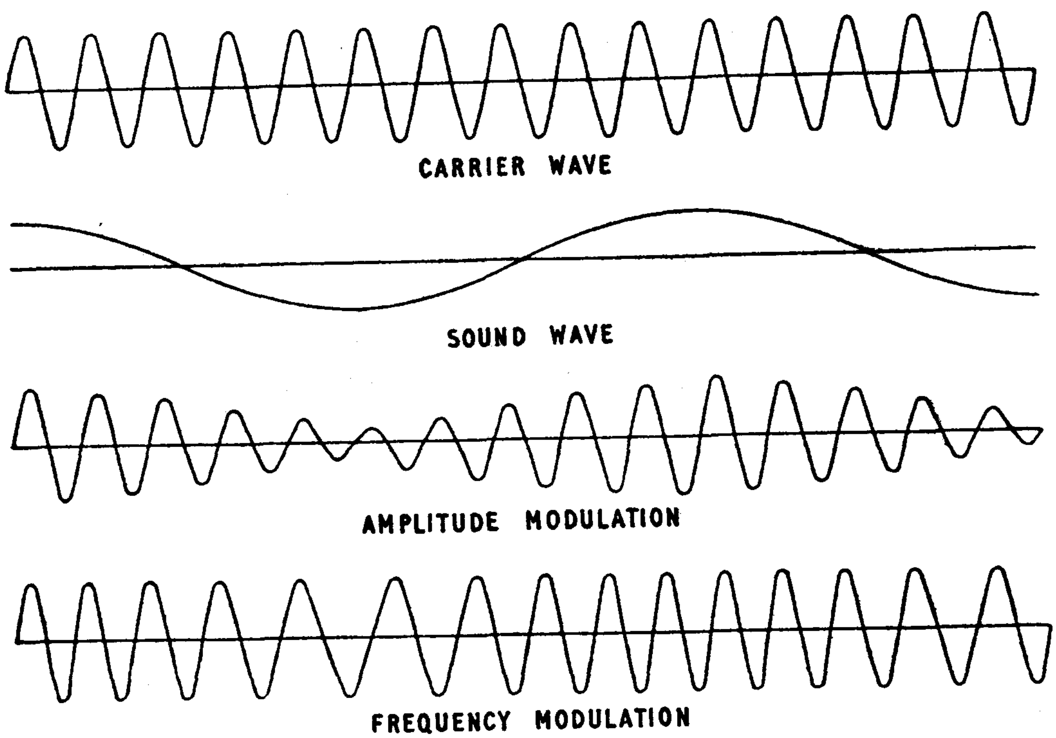


FIG. 10. Amplitude and frequency modulation.

Short Wave Techniques

Electro-magnetic vibration of wave-lengths less than 1 metre cannot be produced in an ordinary valve transmitter, since the wave-length would then be of the same order of magnitude as the structural elements. The transit-time of the electrons in the tubes used (*see* page 78 ff.) would then become comparable with the period of the oscillation and conditions in the tube would no longer correspond regularly to the changes in potential. On the other hand, wave-lengths of approximately 10 cm and less have become necessary in the last few years for the important radar techniques, i.e. for the detection of distant objects. The formation of a ray that has to be reflected from the object back to the receiver requires, as we have already seen,

wave-lengths which are small compared with the "beam transmitter" producing the radiation, and with the irradiated object. These extremely short (decimetre and centimetre) waves are produced in special circuits or—in most cases—by means of "magnetrons" (*see* page 80). The transmitter then delivers a wave impulse of very short duration. This travels from the transmitter to the object and is sent back to the receiver which is located next to the transmitter. The time taken by the signal can be measured by means of a cathode-ray tube (*see* page 82). From it, just as in depth sounding, we can infer the distance of the objects. In this way we can determine fairly accurately the direction and distance of aeroplanes, ships, etc.

The technique of very short electro-magnetic waves has been of especial importance in the measurement of the ion content of the upper stratosphere, and has enabled us to give a physical interpretation of the formation of the Heaviside-layer and the charges in it. The ultra-violet radiation of the sun causes electrons, in layers between 80 and 500 km above the earth, to be split off from the atoms and the molecules of the air, so that there remain positively charged ions and molecules together with free electrons. The density of these charged particles in the ionospheric layer is great enough for the layer to act like a metal towards electro-magnetic waves of certain wave-lengths. The charges resonate and reflect the wave. That wave-length which is only just reflected is a measure of the electron density of the reflecting layer. The height of this layer can again be found from the difference in time between the transmitted and the reflected signal. Using electro-magnetic waves of so short a wave-length that they can penetrate all layers of the ionosphere, investigators have managed to reach the moon and to demonstrate the radiation reflected by it. The reflected signal was received 2·56 seconds after transmission.

For some years we have known with certainty that an electro-magnetic radiation in the realm of the metre and centimetre waves penetrates the earth's atmosphere in the form of cosmic short-wave radiation. Only recently could it be proved that our sun also transmits such very short-wave radiation. A relation has been established between the in-

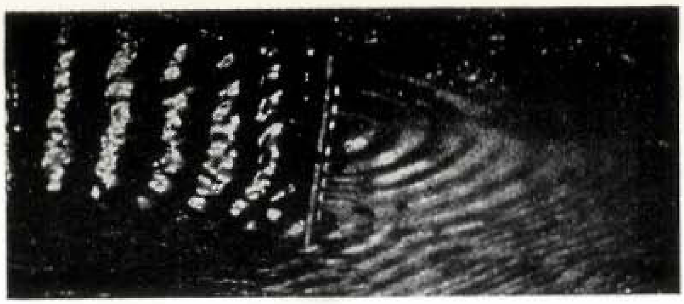
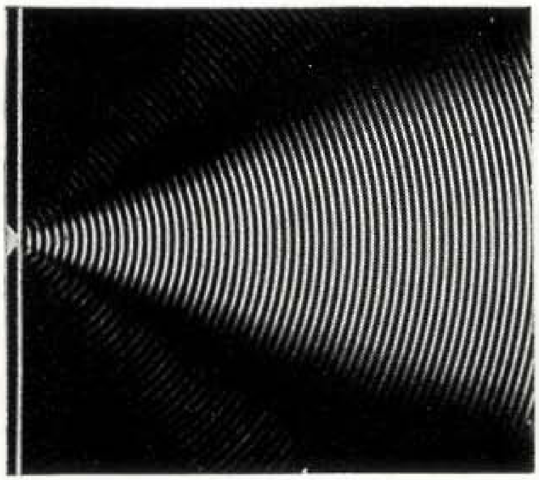
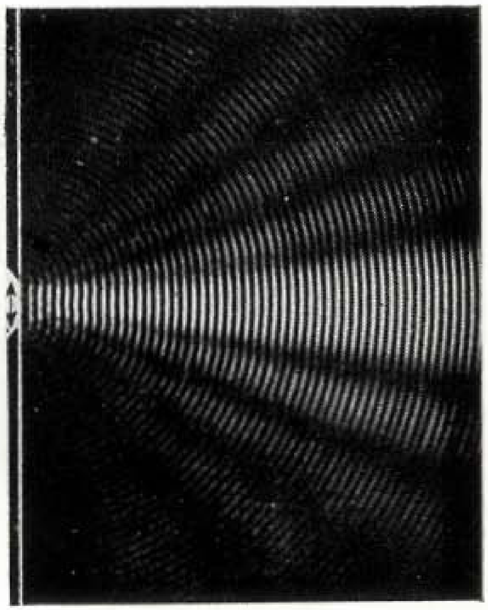


PLATE 1. Diffraction of water waves at a hole. (*After* Grimsehl.)



a



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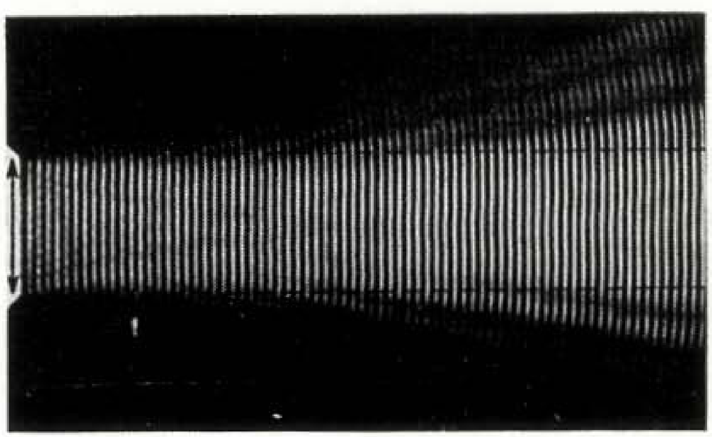

c

PLATE 2. Experimental attempts to limit plane waves by passing them through gaps: (*a*) hole, (*b*) narrow slit, (*c*) broad slit. (*After* Pohl.)

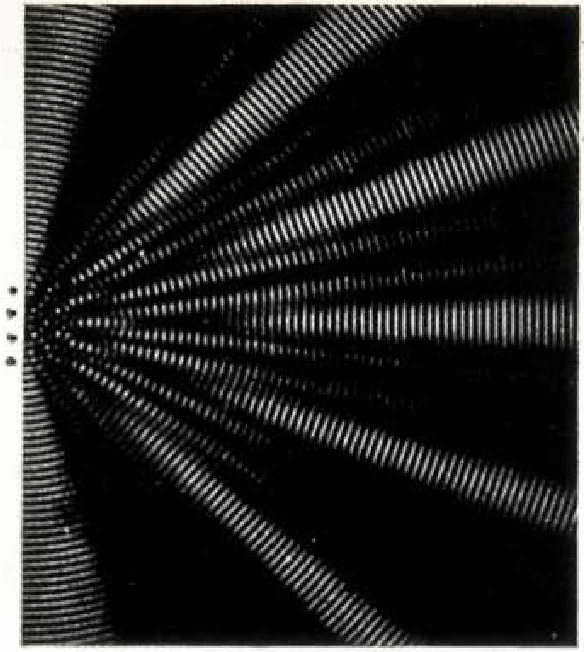

PLATE 3. Experimental attempts to produce interference of four trains of waves with equidistant centres (indicated by points): diffraction grating. (*After* Pohl.)

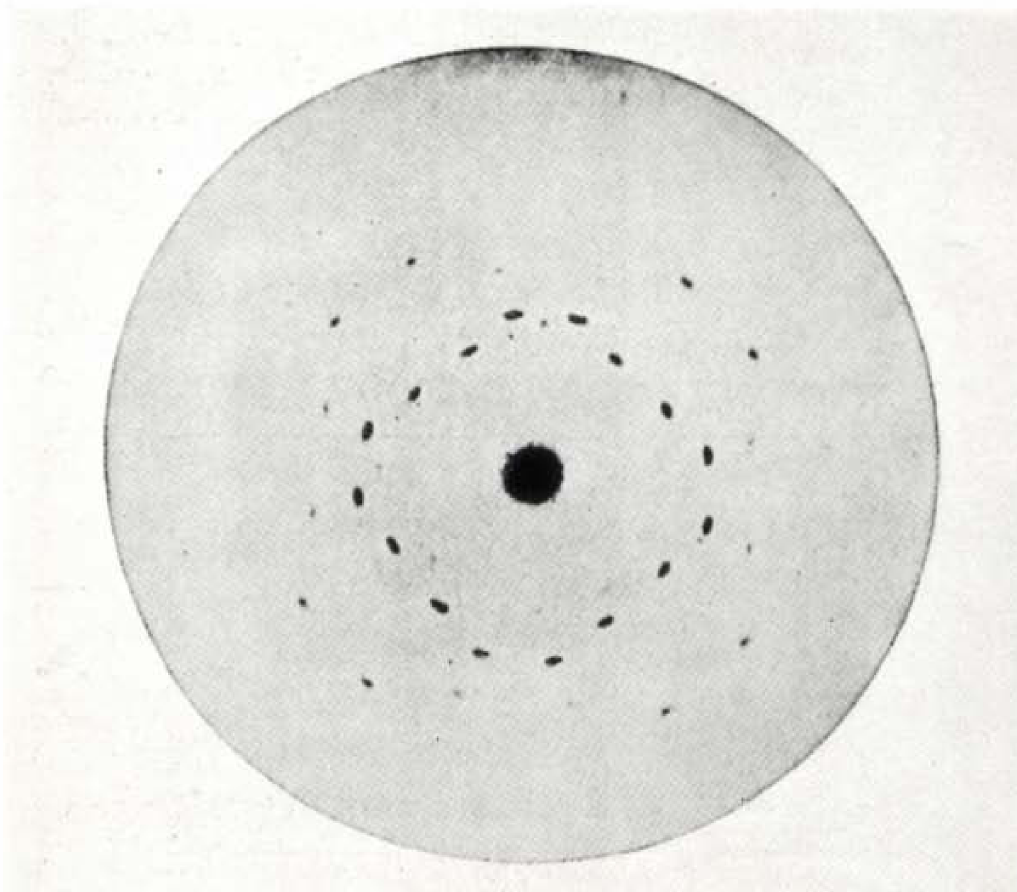

PLATE 4. Laue diagram of zincblende.

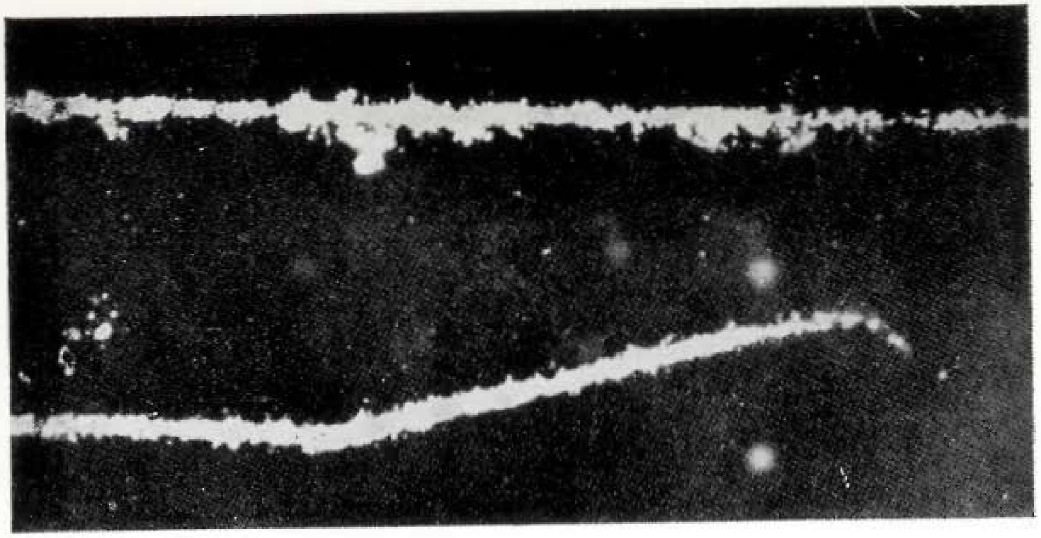

PLATE 5. Individual tracks in the cloud-chamber.

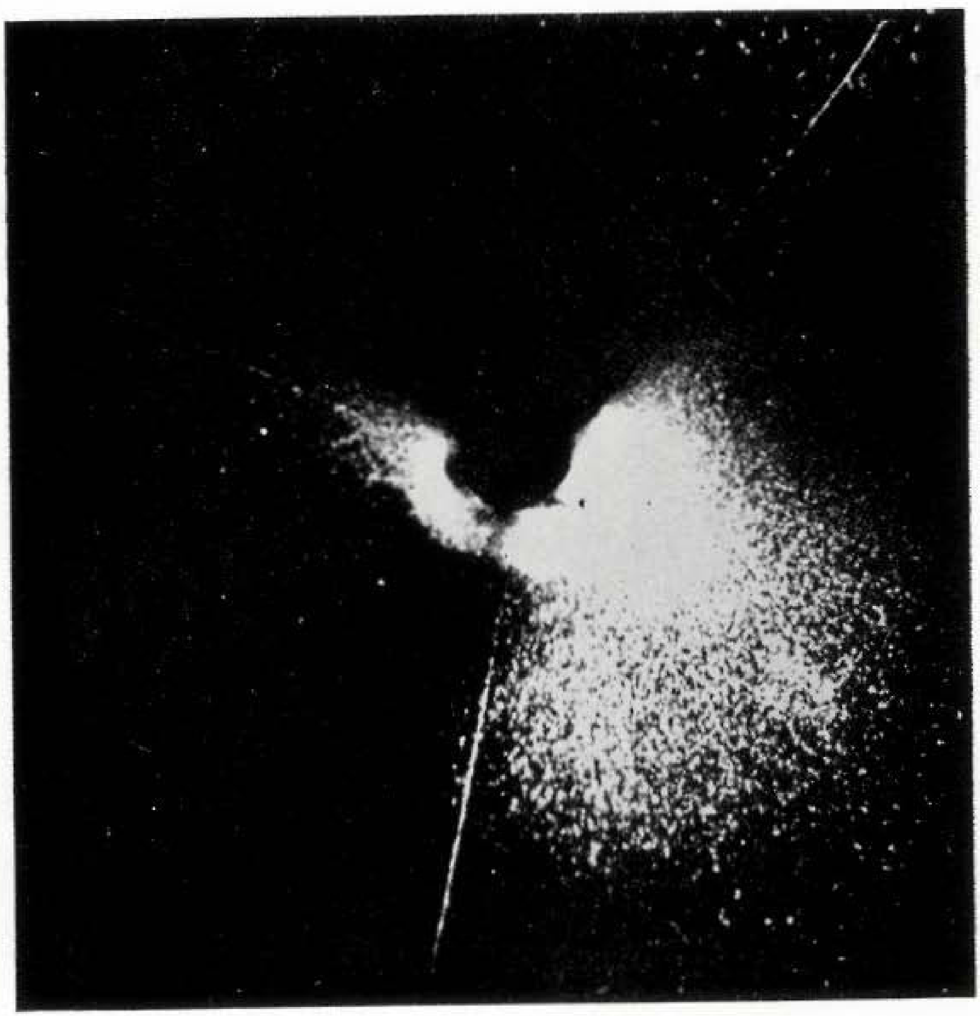

PLATE 6. Protons from a discharge-tube striking a screen. The three trajectories are those of the three alpha-particles which are ejected.

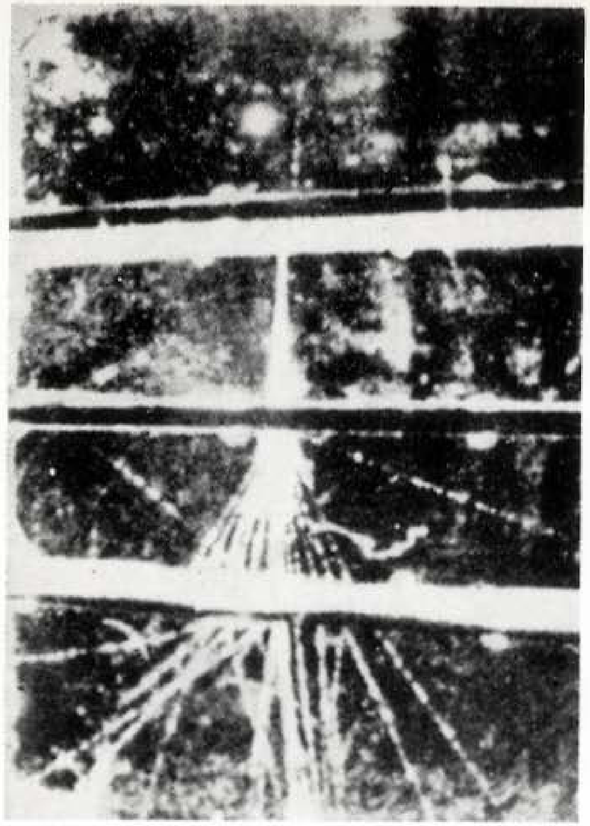

PLATE 7. Shower of high-frequency radiation in the cloud-chamber. (*After* Fussell.)

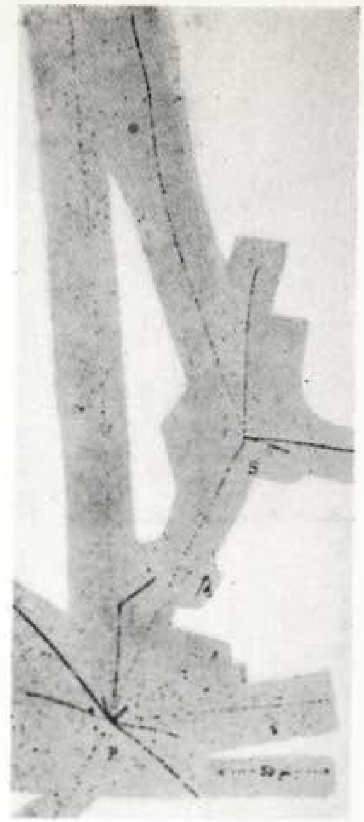

PLATE 8. Nuclear fission caused by a particle of high energy (proton or meson) in which a meson is produced causing nuclear fission in its turn. (*After* Powell.)

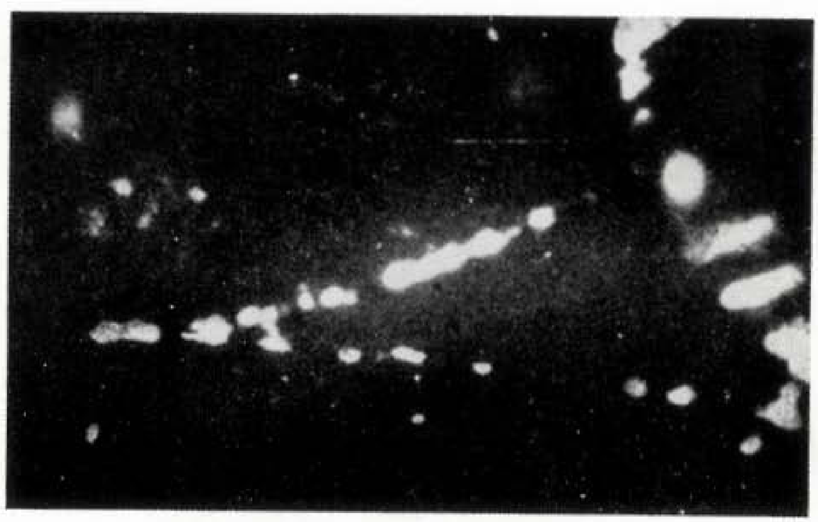

PLATE 9. Transformation of γ-radiation (Plate 7) into a negative and a positive electron. (*After* Joliot *and* Curie.)

tensity of this short-wave radiation and the number, surface area and arrangement of sunspots. All the cosmic short-wave radiation is perhaps the sum of the contributions from single stars in which processes like that in the sun produce short-wave radiation.

Visible Light and Related Fields

A prism divides white sunlight into its spectral colours. However, it not only produces the visible colours of red, yellow, green, blue and violet, but even beyond both red and violet can the existence of energy still be demonstrated. Beyond the red, in the infra-red region of the spectrum, the energy can be demonstrated by a simple thermometer—the mercury is found to be heated by an invisible, i.e. infra-red radiation, and shows a rise in temperature. It is this radiation which is emitted by a warm, invisibly glowing stove and which, for instance, can be absorbed by a screen impenetrable to this radiation. The wave-lengths of the infra-red spectrum range from the limit of visible light (about $0{\cdot}8\ \mu = 8.10^{-5}$ cm) to the shortest wave-length that can be produced by magnetrons—micro-waves—i.e. up to an order of magnitude of one millimetre. The longest wave-length of infra-red radiation hitherto observed is that in the spectrum of the mercury vapour lamp: the radiation has a wave-length of 0·34 mm and already shows all the properties of an "electrical" wave.

In recent times, infra-red radiation has been used technologically. Air drying of lacquer and thin film layers and also of textile fibres and materials after certain preparatory processes, has today been replaced by infra-red drying. The drying time compared with previous methods has already been reduced to a fifth. The success is mainly due to the fact that the long-wave infra-red manages to penetrate to a certain depth of the object to be dried and thus dries the whole layer through its entire thickness. Visible and infra-red lights are generally absorbed and reflected under different conditions. Infra-red photography can be used with advantage in those cases where visible light can show no fine details, or where it is absorbed.

Infra-red photography is used for the investigation of colours, for instance, in the textile industry, in medicine, and in

criminology, for testing paintings, and for photo-microscopy. It has special advantages for landscape photographs since mist and fog are penetrated by infra-red "light", and also for photography in the dark. There are even stars and other astronomical objects which appear much more clearly on infra-red plates than on normal photographic plates. Thus in 1944 Baade, at the Mount Wilson Observatory, managed to resolve the nuclei of the nearest extra-galactic nebulae (for instance the Nebula in Andromeda) into single stars. Many nebulae in our own Milky Way were only properly recognised on plates sensitive to the red.

Microscopes and Telescopes

The properties of visible light, ranging between wavelengths of 0·8 and 0·4 μ are generally known. Optical instruments, concave mirrors and lenses and their combinations in microscopes and telescopes produce a magnification of the angle under which the object appears to the eye. Optical techniques are used to reduce the degree of distortion of a picture over the entire field, and to increase the resolving power of the instruments, i.e. the ability to distinguish two neighbouring points. The resolving power of an optical instrument is limited by the fact that because the light beams are narrowed through the objective, tube, or ocular, etc., two very close points can only be perceived separately if the first diffraction maximum of one lies on the first diffraction minimum of the other (Rayleigh). Since that angle subtended by the two objects when they can just be distinguished is inversely proportional to the diameter of the lens, or in the telescope of the convex mirror, and especially since the brightness of the fixed stars against their background is proportional to the square of this diameter, it becomes understandable that astronomers are building telescopes with ever greater mirrors.

The new telescope on Palomar Mountain in California has a mirror of 200 inches diameter; the mirror receives about a million times as much light as the human eye, and theoretically it can produce a magnification of 20,000 x. However, because of the movements of the earth's atmosphere, this cannot be utilised fully. In time, this instrument will no doubt enable us to measure the proper motions of neighbouring fixed stars

accurately enough to determine whether they are affected by the gravitational effects of possibly existing planets. Above all, the great telescope is meant to give us an accurate knowledge of the structure of the most distant objects of the universe. The technical difficulties in the use of this instrument are very great already. We must consider that its effectiveness depends on the precision with which the mirror is adjusted and with which the temperature is kept constant throughout its entire diameter, for even the smallest and most insignificant difference in temperature produces deformation in its surface, and this causes the image to deteriorate.

In the microscope the maximum resolving power has been reached in practice. The resolution can be increased only if we diminish the wave-lengths used which is not possible with visible light though it can be achieved by means of the electron microscope (*see* page 81). Nevertheless, in the optical industry there are ever new practical improvements. For instance it is now possible to demonstrate elements of structure which are both transparent and colourless, but which differ in their refractive index, i.e. in the velocity with which light passes through them. The difference in the velocity of light in two different media produces small phase differences in the light rays passing through. The latter cannot be detected by the eye since it distinguishes only radiations of different amplitude and not of different phase. In "phase contrast" procedure the phase difference is subsequently brought out by a suitable method—for instance, by the inter-position of a plate delaying the light by half a wave-length, so that clear interference pictures are created and the phase structure is made visible to the eye as an amplitude structure.

Furthermore, beyond the violet of the visible spectrum there is short-wave radiation which is imperceptible to the human eye—namely ultra-violet light. Radiation from the sun contains much ultra-violet light, of which the strong effect on the skin, especially at great heights, is well known. The greater part of the ultra-violet light coming from the sun is however absorbed in the ionospheric layers where it ionises the air. The density of these charged particles formed in space is measured by the reflection of very short electro-magnetic waves as we have already discussed (page 71).

X-rays

The shorter wave-lengths (higher frequencies) of the electro-magnetic spectrum are followed by ultra-violet light, and then by X-rays. During experiments with Lenard tubes, designed for the production of free electrically charged particles, Röntgen discovered a radiation that emanated from the point at which the electrons met the glass wall or the metal part inside, and which had a far greater power of penetration than all previously known rays. Von Laue showed by means of diffraction phenomena in crystals—of which we shall speak in greater detail below (*see* page 137)—that X-rays were of even shorter wave-length than ultra-violet rays. The wave-lengths of X-rays are between approximately 65 and 0·015 m μ.

In penetrating matter X-rays undergo a loss in intensity which, as was shown by all experiments, can be represented by an exponential law—i.e. in layers of matter of equal thickness the same fraction of the penetrating radiation is always absorbed. The absorption depends on the wave-length used, and on the atomic weight of the absorbing medium. It is for this reason that X-rays can be used for examining the human body with great advantage; for the organs which contain heavier atoms than do their surroundings, show as dark regions on a photographic plate. Cavities of the body to be investigated may be filled previously with contrast media containing especially heavy atoms (for instance bismuth), so that they appear on the photograph as a dark shadow.

Similarly, machine tools, etc., may be examined by X-rays, giving a method of testing which does not harm the material. Cracks, gas bubbles, foreign inclusions, etc., can be made very clearly visible by X-ray.

There are electro-magnetic vibrations of even shorter wave-length than X-rays, namely radio-active gamma-rays and the photons of cosmic radiation. We shall deal with these in Chapter 11.

Chapter 8

ELECTRONS

LET us return from the electro-magnetic field to the charge causing it.

It has been noticed that electric charges are freely movable, while magnetic poles can only appear materially tied to the opposite pole. Ampère assumed that all magnetic poles were, in fact, small electric currents, such as electric charges moving round atoms. Today we agree with him. What do we know of charges?

The Foundations

It is an old question whether electricity is a continuous fluid or whether it has an atomic structure. This question could only be decided hand in hand with that of the corresponding question for matter itself. In nineteenth-century chemistry, the idea of an atomic structure of matter gained the upper hand. In electrolysis Faraday's law of equivalences holds. If a current flows between two electrodes that dip into a conducting fluid, then some of the fluid particles are continuously deposited at the electrodes. For instance in a copper sulphate solution, copper is deposited on the one plate and the acid radical on the other. Since an acid radical cannot exist independently, it reacts chemically with the electrode and if this is of copper, it reforms copper sulphate which goes into solution. The deposition of the solute at the electrodes is interpreted by assuming that the current in the fluid is the charge transported by the electrically charged atoms themselves. Now Faraday's law states that with a given quantity of matter there is always transported a given charge, such that a given quantity of charge corresponds to every deposited molecule, no matter what it is. From this Helmholtz and Stoney concluded that the electric charge itself appears in atomic particles. The magnitude of this elementary electrical charge has been measured in different ways.

Now the question arises whether the elementary electric charge must always be tied to an atom, or if it can travel freely through space. Today we know that the latter is the case. This freely moving charged particle is called the electron. We observe free electrons, for instance as cathode rays, when we send an electric current through a highly evacuated vessel (a Geissler or Crooke's tube).

Now a moving electron is equivalent to an electric current on which a magnetic field can exert a force. From the deviation observed, it is concluded that the electron must have a negative electric charge. As we shall see later (page 98), every atom contains a certain characteristic quantity of electrons so that electrons are present in every body. In metals there are always some electrons moving freely between the atoms. When an electric field is applied, they begin to wander through the metal. Every change of position of the charges is noticed as an electric current. If the applied electric field becomes greater, a greater energy of translation is imparted to the electrons in the metal because of the more violent collisions taking place in the conductor; the latter becomes heated, a fact which is made use of in electric fires and electric bulbs.

Electron Valves or Tubes

A good high vacuum is practically a perfect non-conductor, since in it no carriers of electricity are present. If a metal is heated to a high temperature in a vacuum, electrons can be expelled from it and in moving through the vacuum, they form an electric current. This is due to the fact that the electrons moving between the atoms of the metal have obtained such a velocity, that their kinetic energy is great enough to overcome the molecular forces of attraction and so they may leave the metal surface. However, the mean velocity of the electrons in the metallic conductor is not high enough to cause more than a very small percentage of the electrons to be ejected. For this reason the very large number of electrons in the metal is not appreciably reduced. Nevertheless, the electrons leaving the metal surface can produce considerable currents. Electrons can only emerge from cold metal surfaces when they are acted upon by so high an electric field (approximately 10^7 volt/cm and more), that the molecular forces of attraction are overcome by it.

If we apply an alternating current to a vacuum tube in which there are one (electrically) heated and one cold electrode, then the current of electrons can flow in one direction only. If we apply a negative potential to the hot electrode, electrons can travel only from this electrode to the positive electrode. With reversed polarity, there can be no current of electrons at all since the cold electrode cannot transmit electrons (rectification).

In the X-ray tube the electrons emerging from the glowing cathode are concentrated on the anode, on as small a focus as possible. This is done by means of a special auxiliary electrode in the form of a cylinder (see also ray focusing in the cathode-ray tube, page 83), where the electrons produce the X-rays. The electron collisions generate a great deal of heat—99 per cent of the electron energy in collision is not changed into X-rays but into heat—and the anode must be artificially cooled.

By including further electrodes between the glowing cathode and the anode, it is possible to produce a "steering" of electron currents a process which is practically free of inertia, and which is useful in many physical and technological problems. In the three-electrode-tube (triode) a mesh-like electrode called the grid, is put in circuit between cathode and anode. If the grid is given a strong negative charge, the electrons emerging from the cathode cannot overcome the negative grid potential and therefore cannot reach the anode: there is no current in the valve, the valve is "blocked".

From a certain anode potential upwards—and increasingly with greater potential—the electrons that would otherwise lie in front of the cathode as space charge clouds, can now pass through the grid (working range of the triode) until finally at a given (not very high) positive potential, the current between the cathode and anode remains constant (saturation current). This happens when all the electrons leaving the cathode reach the anode. By means of small changes in the grid potential, considerable changes in the anode current corresponding to the change in grid potential can be produced in the working range; in this way the anode current is controlled. Because it can be used as a relay and amplifier, the electron valve has become the most important means of news transmission. For special

purposes further grids can be put in the circuit, or several electron valve systems can be combined in one valve.

For the production of electro-magnetic waves with wave-lengths of not less than 1 metre, normal electron valves with the usual circuits no longer suffice. Here electron valves with special circuits must be used or, for greater power, special tubes or valves must be employed, for instance magnetrons in which the electrons go into a state of vibration, producing high frequency current alternations between the anode and the cathode.

We have already seen that when the temperature of a metal in a vacuum is raised some of the electrons have such high kinetic energy that they can leave the metal. However (as we shall explain later) an increase in kinetic energy can also be produced through electro-magnetic radiation, light, X-rays, etc. If, for instance, light falls on a cathode, on which an alkali metal has been deposited, then even when a low potential is applied to the anode in a vacuum, electrons will emerge from the cathode (photo-electric effect); there can be shown to be a current between cathode and anode. To demonstrate the presence of very small numbers of electrons due to this photo-electric effect the electron current originally transmitted is amplified, by causing the primary electrons to expel secondary electrons from a further electrode and so on in a third, fourth electrode, etc. This produces an avalanche-like multiplication. With these photo- (or secondary electron) multipliers we can obtain an intensification factor of up to 150,000 for measuring weak light sources.

The expulsion of electrons by light can take place not only in a vacuum and on the surfaces of metals, but also inside transparent materials, for instance, inside a crystal. Under the influence of an applied electric field the electrons begin to travel and thus lead to a greater conductivity of the material.

Electron Optics

Since the electron carries a charge, its direction of motion can be influenced by electric and magnetic fields. An electron propelled into the space between the two plates of a parallel-plate condenser is attracted by the positive plate. Its original

rectilinear trajectory is therefore curved towards the positive plate. In a homogeneous magnetic field at right angles to its motion, an electron describes a circular path which—as we have seen (page 77)—can be explained by considering the moving electron as a current on which, according to the law of induction, a corresponding force is acting. We can now arrange the electric and magnetic fields in such a manner that the electrons spreading from a given point in different directions can be focussed, just as by optical lenses in the case of visible light. The electric and magnetic "lenses" produced in this way have

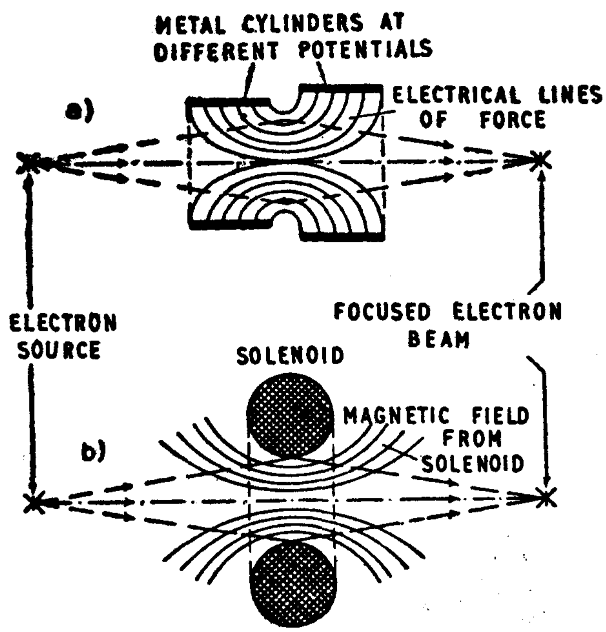

FIG. 11. (*a*) Electric, (*b*) magnetic, lens.

the great advantage over optical ones that their "focus" can be altered at any time by variations of potentials and currents.

By means of electric and magnetic lenses we can build microscopes which like optical microscopes magnify very small structural elements, but which have the further advantage (because of the very small wave-lengths of the electrons—see below) of having a far greater resolving power than an ordinary microscope (*see* Figs. 11 and 13).

Electron or ultra-microscopy is of special importance in chemistry and medicine. Today already the smallest viruses, protein and fibre structures, large organic molecules, fine

structures of metal surfaces, etc. can be seen in the electron-microscope. Theoretically, we should be able to demonstrate even a molecule or an atom in the electron-microscope, but not all the practical difficulties have been overcome so far.

In the last few years a field electron microscope has been developed in which the spherical cap of a very fine metal point (as negative electrode) is made to throw an image on a screen. At the metal point there is a field of about 4.10^7 V/cm so that the electron can be expelled by means of field emission and is then propagated from the surface radially and rectilinearly. The linear magnification in this arrangement is between 10^5 and 10^6, the resolution about 15 to 20.10^{-8} cm, i.e. approximately 10 hydrogen molecule diameters. It can however be increased even further under special conditions (for instance by the adsorption of flat molecules on the metal point) (*see* Fig. 13).

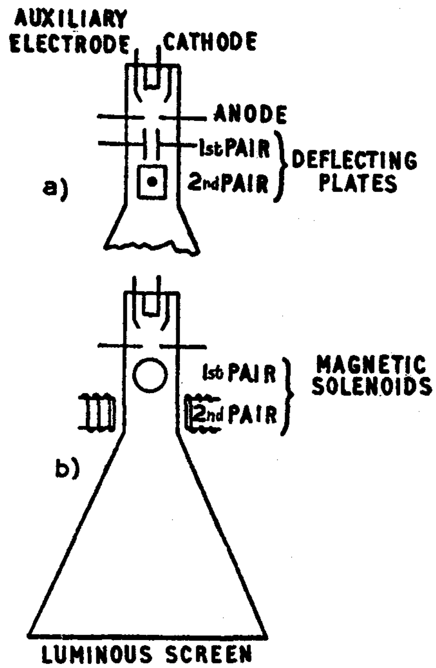

FIG. 12. Cathode ray tube with (*a*) electric deflecting plates, (*b*) magnetic deflection arrangement.

Cathode Ray Tubes

In electron optics there are also used cathode ray tubes: electrons produced by a glowing cathode are attracted by a metal anode placed close to the cathode, and having a small hole in the centre through which the electrons can pass. To produce a very fine electron beam the cathode is made as pointed as possible and in its immediate vicinity there is placed an auxiliary electrode—which is generally given a weak negative charge ("Wehnelt-cylinder") (*see* Fig. 12).

The electron beam falls on a screen and produces a bright spot on it. If we allow the stream of electrons to pass through a pair of condenser plates in its path, it will be deviated by an amount corresponding to the magnitude of the potential applied to the condenser, and the bright spot on the screen will

be deviated more or less from its original position. If we arrange a further pair of plates perpendicular to the first pair, we can study the relation between two magnitudes. In many cases, the physicist uses the horizontal displacement of the beam as the *time* axis. The spot on the screen is made to travel in the horizontal direction, with a displacement proportional to time, so that any simultaneous vertical deviation can be conceived as dependent on the time. For instance it can then follow very rapid potential impulses, and it is an essential measuring

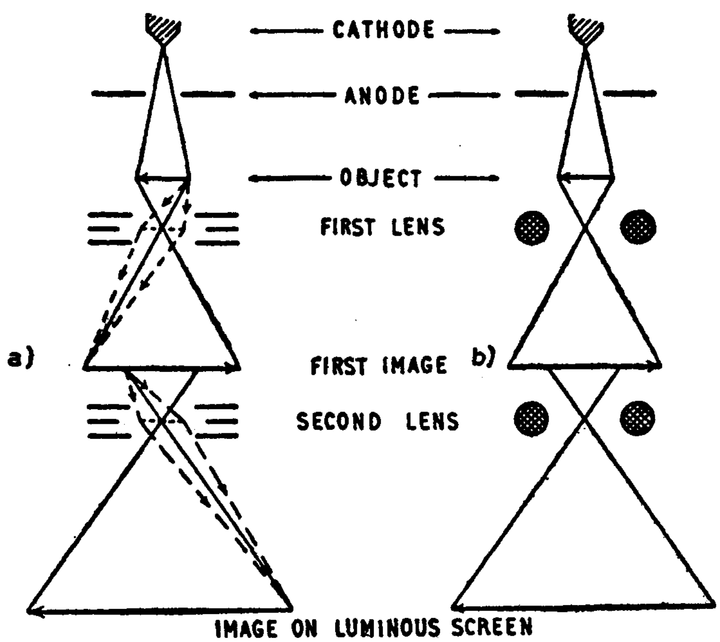

FIG. 13. Scheme of the electron microscope with (*a*) electric, (*b*) magnetic, lenses.

instrument for rapid variations in current and potential. In a similar way the deviation of the beam can also be produced by the magnetic fields set up by the currents to be measured in solenoids mainly outside the tube itself.

The technical significance of the cathode ray tube lies in its application in television and radar. In television the spot is directed by the mutually perpendicular pairs of plates so that, like handwriting, it runs along a regular sequence of ruled lines. While the spot traverses the screen, its brightness is varied according to that of the corresponding picture. Because of the short after-glow of the screen, and because the eye retains an after image for a short time, we gain the impression of a full

screen picture. The B.B.C. television service uses 415 lines and 50 pictures per second.

In radar the reflected signals are reproduced on the screen of a cathode ray tube in a position depending on the direction of the beam. Their brightness corresponds to that of the reflecting object, so that if the direction of the reflected wave is correctly adjusted with the displacement of the spot of the cathode ray tube, an undistorted electron-optical image of the irradiated surface appears on the screen of the cathode ray tube. This image may be used as a map.

Chapter 9

RELATIVITY THEORY

RELATIVITY theory can be considered as the completion of the field physics inaugurated by the electro-dynamics of Faraday and Maxwell. However, from a methodological point of view, it is the first conscious step of a new method of thought in the theoretical physics of the twentieth century.

Classical and Modern Physics

We call the physics of the nineteenth century "classical physics". This name implies both a recognition and a limitation. Classical physics itself hoped to discover basic laws of nature which were to be valid always and everywhere. Today we believe that although the laws of classical physics hold always, they do not do so everywhere; more exactly stated: they have a certain domain of validity. Within this domain they are correct and final for all time. Never will eclipses of the sun be calculated by laws other than those of Newton, never will we construct a steam-engine according to laws other than those of classical thermodynamics. According to other laws would here mean according to contradictory ones. The same laws can of course be formulated differently. Furthermore new laws may be discovered which whilst having a greater domain of validity than those of classical physics, nevertheless do not differ from the classical laws within the domain of the latter—at least not in an experimentally determinable way. These new laws would then have a greater domain of validity in which that of classical physics is included.

This state of affairs can be clarified by means of an example. Classical physics can be compared to an accurate map of a small town. This map is based on some general assumptions. For instance, it must be drawn on a flat piece of paper, and therefore supposes that the earth is flat. Nevertheless, mountains, valleys, etc., can be projected on to a well-defined (horizontal) plane of reference (for instance, that of the market-

place). Those who know no more than this will readily agree with the assumption that the earth is everywhere flat, even outside the known domain of the small town. Now, modern physics can be compared to the recognition that the earth is round. The world picture of the small townsman is thus completely changed. Nevertheless, every single empirical recognition expressed in the town plan remains completely valid. Since, within the domain of the town, the curvature is immeasurably small, we can here justifiably assume that for all practical purposes the earth is flat. We say that the general theory (in this case that of the spherical nature of the earth) changes in the limiting case (here the limiting case of a small extension) into the special theory (here that of the flat earth).

The example shows that the delimitation of a particular domain of validity is not sharp, and is only possible after laws of greater validity have been recognised. Only if we know the spherical nature of the earth and its (approximate) diameter, can we say how far we may go from the market-place of our small town, for the difference between the true shape of the earth and that of a plane still to remain within a given limit. We usually choose this limit so that it corresponds to the degree of accuracy of the measurements we are making.

Our example does not show the inevitability of the classical point of departure. A man can leave the town in which he was born, he can travel around the earth: the spherical earth lies, if somewhat abstractly, within the realm of his possible immediate experience and of his powers of imagination. Modern physics, however, deals with objects which are quantitatively beyond direct perception (atoms cannot be seen, an object flying past at the velocity of light cannot be followed with the eye, etc.), and furthermore its laws state that no rule of similarity exists by means of which these objects could be compared with materially perceptible ones. The laws of modern physics differ structurally from those of the perceptual world. While we can use a globe as a model of the spherical earth, which we have also never been able to perceive as a whole, there is no model for the objects of relativity and quantum theory. It is for this very reason that we cannot dismiss the ideas of classical physics simply as being merely a preliminary step in physics. Modern physics too is based on experiment.

Experiment, however, is only using our senses. All I have experienced I must be able to describe in a material and conceptual manner. Classical physics describes the utmost limits up to which the concepts of physics can be represented by perceptual models. Immediate sense experiences therefore, even in modern physics, must always be expressed by means of the concepts of classical physics.

It may sound paradoxical that a physics which transcends the domain of validity of classical physics describes all experiments in a classical manner. It is no less paradoxical than the fact that while basing ourselves on sense experience we can transcend the limits of sense perception. That this can be done is based on the laws governing the connections between natural processes; without this connection there could be no conclusions from what is perceived to what is not perceived, i.e. in the final analysis no human life would be possible. This interconnection is also assumed in the realm of the objects of modern physics, and we confirm it by verifying the predictions made on its basis. However, we no longer formulate it by means of perceptual models, but rather we use an abstract "law of transformation". By this we mean:

A single experiment always gives no more than one aspect of events: a look at the earth from one particular tower, the measurement of one particular property of an atomic structure. A model or a law connects these aspects. From the spherical form of the earth we can deduce how the earth would look from every other tower. The model permits the transformation of one aspect into every other one. A vector, such as the velocity of a body, has different components in every different system of co-ordinates. The co-ordinate system chosen by the observer characterises the aspect. What interests us here is how to transform the components from one co-ordinate system to another, and especially, which data do not depend on the co-ordinate system at all (for instance, the length of the vectors). We call these the invariants of the co-ordinate transformations.

Now in modern physics the transformation laws of the aspects are no longer put down in conceptual models. Their character as laws of transformation thus emerges more purely and at the same time more directly. This is indicated by the

name itself: relativity theory means no more than that certain physical statements are related to the chosen co-ordinate system.

Perhaps I may be permitted to point out how much this method of thought differs from relativism in the common usage of the word. The relativist dissolves the concept of truth by teaching that what is "true" depends on the point of view of the subject. The contemporary physicist knows well enough that one can see different things from different points of view, but he searches for the laws that determine what is seen from which point. It is just in these laws that he finds that form of truth that can be understood by us. We can choose the point of view, but what we then perceive no longer depends on us.

Special Theory of Relativity

The problem of the relativity of motion which we left open in our discussion of mechanics was brought into a new light by electro-dynamics. We can follow its development in two stages characterised by the works of Einstein, by concerning ourselves first with inertial motion, and then with all kinds of motion.

The question whether we can attribute an absolute significance to the concepts of rest and motion, or whether they are only relative to their respective reference system, that is, if they are to be defined purely as aspects, has remained unsolved in classical physics. It is true, Newton postulated the existence of absolute space and absolute time in which all bodies moved; rest and motion have an absolute meaning as far as these bodies are concerned. Leibniz and, 200 years later, Mach noted that this doctrine was no necessary part of classical physics, but an additional metaphysics. For in classical physics there is no experiment to determine whether a body in an absolute sense is at rest or in uniform motion.

This "principle of relativity" of classical mechanics is, as we shall see at once, a consequence of the law of uniform motion. It is thus an empirical statement itself, and must therefore be strictly distinguished from the commonplace that we can describe the condition of motion of any chosen body at will: for instance, describing a circus acrobat swinging on the trapeze as at rest, and the motion of all other bodies in this

co-ordinate system as rushing past him. In such a co-ordinate system Newton's laws are not valid. For instance, in the acrobat system a body on which no force is working, does not remain at rest or in uniform motion; rather will it execute complicated screw-movements which translated into a reasonable system, are the mirror images of the movements of the acrobat. "Equally privileged" co-ordinate systems for which there is no experiment that can determine a preference, are only those in which Newton's laws are valid.

People in a railway train travelling with constant speed and without any vibration can only tell whether they are moving by looking out of the window. This means that they cannot determine their speed absolutely, but only relative to the environment. This is not at all obvious as can be seen from the fact that acceleration can be determined absolutely. If the train should suddenly brake, standing passengers will fall over and the suit-cases be thrown out of the racks. Acceleration can only be produced by forces, and if we should use an accelerated system of co-ordinates, i.e. that of the braking train, then bodies like travellers and suit-cases, which obey the law of inertia, behave as if forces were working on them. The relativity principle is therefore a consequence of the fact that only the second derivative of place with respect to time is determined by the force, i.e. through interaction with the environment. Thus zero acceleration is measurably different from every other acceleration; for zero velocity or zero place-co-ordinates, the corresponding statement is not valid.

Newton based his concept of absolute space empirically on the fact that accelerations can be determined absolutely. Whatever this might mean (*see* pages 92-93) in any case the relativity principle too is a consequence of Newton's law and the assertion of absolute space is therefore, in so far as places and velocities are concerned, basically unprovable in classical mechanics. (For the present we shall be content to compare systems which move in rectilinear uniform motion with respect to one another, where Newton's laws are valid. We call them "inertial systems".)

This state of affairs was apparently changed by electrodynamics. In it there is an exceptional velocity: the velocity of light. It is independent of the state of motion of the light

source: the luminous body does not emit light corpuscles which, like bullets sent by a flying aeroplane, take part in its motion, but produces waves in the surrounding medium—the electromagnetic field—or using, as in the past, a material picture, in the "ether". It was thought reasonable to consider this ether as a material transmittor of Newton's absolute co-ordinate system.

Experiments were designed to demonstrate motion with respect to this ether. Michelson is responsible for the famous experiment to measure the motion of the earth with respect to the ether. The result, as in all similar experiments, was negative. The principle of relativity also holds in electrodynamics. Equally valid is the principle of the constancy of the velocity of light, i.e. that the measured velocity of light neither depends on the velocity of the light source, nor on the velocity of the observer.

For this reason, Einstein raised the two principles of relativity and of the constancy of the velocity of light to the status of basic postulates, and showed that they did not contradict each other if and only if previous conceptions of space and time were discarded. This perhaps can be most easily shown by the following: A light wave seen by observers moving differently, always shows the same velocity. This means that any chosen velocity added to the velocity of light would again give the velocity of light. But how do we compose velocities? Velocity is the path traversed in unit time. Hitherto we assumed naïvely that the length of a measuring rod and time measured with a clock, were inherently constant magnitudes. Einstein, however, found that if the two postulates were true, lengths and time intervals must necessarily depend on the motion of the reference system in which they are measured. This had already been postulated *ad hoc* by Lorentz as a means of explaining the Michelson experiment. For instance, moving measuring rods become shortened when considered from a stationary reference system, and moving clocks seen from the stationary reference system go more slowly. We cannot enter into the mathematical details here, but it may seem reasonable that thus even the concept of velocity depends on the reference system, in a way different from that of classical physics.

Einstein's achievement was to show that even the relativity

of length and time intervals was the necessary consequence of the relativity of another concept, of that of the simultaneity of distant events. Two events, which seen from one reference system occur simultaneously, do not need to do so when seen from another reference system. We cannot enter into any greater detail, but we can say generally: Einstein recognised that "length", "time interval" and "simultaneity" belong to the aspect, and that only the "law of transformation" (the Lorentz-transformation) set out in the two basic postulates, is the absolute physical assertion at this stage of physics.

Energy and Mass

A consequence of this theory deserves special mention: the equivalence of energy and mass. We have called the law of the conservation of energy one of the basic laws of physics. Of similar importance is the law of conservation of mass, on which all quantitative chemistry is based. By means of the relativity theory, both laws of conservation were fused into one. In order to satisfy the demand that the law of the conservation of energy remain valid in all reference systems moving in uniform rectilinear motion with respect to one another, it follows from relativity theory that the mass of a body in motion, seen from a non-moving reference system, is dependent on its velocity, and, furthermore, that to all masses at rest there must be assigned an energy content (E), which only differs from the mass (m) in the factor of the square of the velocity of light (c^2): $E = mc^2$.

In the case of velocities usually considered in macroscopic processes, the change of mass with velocity cannot be determined in practice. However, the more the velocity of a body approaches that of light, the greater becomes its mass, and thus its resistance to acceleration, until the mass—according to the theory of relativity—becomes infinitely large at the velocity of light. The velocity of light is thus the upper limit of the velocity of any body whatsoever; no bodies can have any greater velocity.

The equivalence of mass and energy has been confirmed in atomic physics. The energy of some nuclear reactions is so great that the corresponding change in mass of the atoms can be measured directly.

General Relativity Theory

Since the concept of absolute space has been discarded in respect of positions and velocities, it does not seem satisfactory to retain it for accelerations. On the other hand, it is an empirical fact that accelerations can be determined even without comparing them with motions in the environment. What does this mean? Let us consider Newton's classical pail experiment:

The simplest accelerated motion (bearing in mind that velocities are vectors, *see* page 22) is uniform motion in a circle. In this case inertia can be observed as centrifugal force. We can say of two bodies rotating relative to each other, which of them is really turning: it is that in which a centrifugal force can be observed. Newton demonstrated this in his pail experiment: a bucket containing water is freely suspended by a string; the bucket is rotated and as long as the water itself does not rotate, the water surface remains at rest. When, however, the water starts rotating, it climbs up the wall of the bucket and thus reveals the presence of a centrifugal force. In other words, it was not the movement of the water relative to the bucket (for this was the case only as long as the bucket turned and the water stayed at rest), but the rotation against absolute space which produced centrifugal force. On this experiment Newton based his conviction that absolute space is a reality in itself, capable of producing physical effects.

Mach criticised Newton's conclusion. He noticed that Newton had not proved that this centrifugal force could not have been produced by motion relative to the walls of the room, to the earth, or to the aggregate of the most distant stars. Today we know that it cannot be the circular motion relative to the stars of our Milky Way that is the cause of centrifugal force (for the stars of the Milky Way move in orbits implying a normal centrifugal force). On the other hand, motion considered relative to the aggregate of the galaxies might be responsible.

Einstein took over this question of Mach's and adapted it to the fact that in more recent physics we do not assume any direct interaction between objects separated in space. He therefore introduced a field transmitting the interaction, and found that this field was probably identical with the gravitational field. This is plausible because of the empirical fact that the

mass of a body can be defined in two completely independent ways leading to the same numerical result: either as the constant proportional factor between force and acceleration in Newton's second law, or as the constant determining the gravitational interaction of the body with other bodies (the equality of inertial and gravitational mass). From this fact follows, amongst other things, that all bodies fall at equal speed in a vacuum: although a body of greater mass is attracted more strongly by the earth, it offers a greater inertial resistance to this force. It follows that in the case of a body falling freely in a gravitational field, neither the gravitational field nor the acceleration of the body can be determined without reference to the motion of the environment: we can replace a gravitational field by an acceleration and vice versa. All processes inside a uniformly accelerated body take place just as if the body were at rest in a gravitational field. Einstein therefore postulated the basic equivalence of gravitational fields and accelerations.

This equivalence allowed him to work out a theory of the behaviour of matter in any accelerated co-ordinate system, and in any gravitational field. This theory is mathematically too complicated to be given here. Einstein showed that this equivalence could only be strictly valid if one assumes that the true geometry of space deviates from Euclidian geometry in having a curvature which varies from place to place. He introduced two fundamental physical quantities into his theory: matter and the gravitational field, which give the structure of space at any point considered. He finally formulated two basic equations: one which shows how matter behaves in any given gravitational field, and a second which shows what gravitational field is produced by a given distribution of matter.

The Ideas of Newton and Einstein

We still want to pose the question whether this point of view is opposed to that of Newton. It does refute his opinion that space is absolute, a ready-made "lodging house" into which matter has but to move. Newton has, however, been proved right as against Leibniz and Mach: space is a reality which can have physical effects. These effects are attributed by Einstein to the gravitational field which is responsible for the curvature of space. Einstein's equations can be expressed thus:

the space structure is responsible for the particular motions of matter; and matter in turn determines the space structure.

However, this does not fully answer Mach's criticism of Newton's ideas. The gravitational field is not necessarily fully determined by the distribution of matter. It is possible that infinite space contains only a finite quantity of matter, and that space at infinity becomes Euclidean. In that case, it would not be the motion of matter relative to other matter, but relative to space at infinity which, in the final analysis, would induce a centrifugal force. Einstein, however, has given a possible model of the Universe in which there is a finite total volume of space without space itself being bounded. An analogy of such a space is the surface of a sphere on which a "straight" line finally runs back into itself. Such a space could, for instance, have a constant density, and consequently constant curvature in its medium. So far it has been impossible to decide whether this model corresponds to astronomical reality.

The General Theory of Relativity predicts three empirically verifiable phenomena: the displacement of a light ray in a gravitational field, a shift to the red in the spectrum of a source in a gravitational field, and the deviation of the orbits of the planets about the sun from ellipses (precession of the perihelion). Although all three effects can only be measured with great difficulty, they have been demonstrated conclusively.

PART IV: ATOMS

Chapter 10

THE FOUNDATIONS

ATOMIC physics, in the contemporary sense of the word, presupposes the existence of atoms, and it is concerned with their internal structure, with their transformations, and with the general laws of nature involved. To assess the contemporary state of our knowledge, it is best to review the stages leading up to it.

The Development of Atomic Physics

Materialist philosophers had long believed that all reality is the interplay of the smallest, indivisible particles of matter (atoms). An explanation can only be considered satisfactory if it does not assume everything which it wishes to explain. Were atoms as coloured, as scented, as spirited and as fateful as is the world of our physical life, they would not have enthralled the philosophers. It appeared that atoms had to be different from the objects composed of them. On the other hand, one did not wish them to be so different that they became inconceivable, and thus ceased to be a means of explanation. Thus there arose the idea of the primary and secondary qualities of matter. The primary, such as extension, mass, impenetrability, were to be attributed to the atoms themselves, and the secondary, such as colour, smell and all other imponderables were supposed to be produced by the interaction of the atoms with the perceiver.

Clear-thinking philosophers such as Leibniz and Kant saw that the assumption of the indivisibility could hardly be reconciled with the primary qualities assumed. Indivisibility is the only property of atoms which does not derive from comparison with sense experience, and it is precisely this indivisibility which is the most important point in the whole atomic picture. Unlimited divisibility is one of the aspects of the mysterious inexhaustibility of the world in which we live. This mystery was to be solved by the atoms. However, is it not true

that what has dimensions must be divisible into parts? Why should just certain of these very definite parts be indivisible?

In its happy naïveté, natural science of the nineteenth century forgot about this problem and created the basis for a broad, empirical exploration of the atoms. On this basis some of the true properties of the atoms were discovered in our century, and with them the old problems of philosophical atomic theory.

Since the time of Dalton, atoms have served as the explanation of the law of constant proportions in chemistry: water, which has the chemical symbol H_2O, consists of molecules, each of which contains two atoms of hydrogen and one atom of oxygen. All hydrogen atoms are alike just as are all oxygen atoms. Stereo-chemistry goes further and is concerned with the spatial arrangements of these atoms in the molecule.

The role of atoms in the physical theory of heat has already been considered as has also our recognition of the atomistic structure of electricity.

Further developments of atomic physics have proved by direct methods the existence of the structures called atoms by the chemists (*see* page 120 ff.), and they have also proved their divisibility. This development took place through the interplay of experimental and theoretical discoveries. These two lines of approach can be followed separately for some part of the way.

Radio-activity and Quanta

The most important experimental impetus was the discovery of radio-activity by Becquerel, and its investigation mainly by the Curies and by Rutherford. It was shown that radio-activity is the spontaneous mutation of atoms. In 1911, Rutherford produced an atomic model based on his own experiments and those of his pupils: the atom consists of a very small nucleus (of diameter 10^{-12} cm) which contains almost the entire mass of the atom and which has a positive electric charge, and of a shell of negatively charged electrons which, under the influence of electrical attraction, revolve around the nucleus at a distance of roughly 10^{-8} cm. This revolution can be likened to the planetary orbits around the sun. The number of electrons in the shell of a particular atom is equal to its atomic number in the periodic system (*see* page 136). Radio-active

mutations are changes in the atomic nucleus. It emerged from further experimental developments of nuclear physics (*see* page 111 ff.), that the atomic nucleus consists of two kinds of particles: positively charged protons and electrically neutral neutrons. The charge on the proton differs from that on the electron only in sign. It is therefore the number of protons in the nucleus which actually determines the chemical nature of the element, for it determines how many electrons can be bound to the atom in its normal, electrically neutral, state. Radio-active mutation thus corresponds to a transformation of chemical elements.

This simple picture, however, as Bohr soon came to realise, is irreconcilable with the ideas of classical physics. An electron revolving around a positively charged nucleus is equivalent to a small dipole, and this should constantly send out electromagnetic waves into space. The electrons would thus have to emit energy until they dropped into the nucleus. The atoms would then neither be stable nor equal. It was Bohr's achievement that he stuck to this model in spite of this contradiction, and that bearing the latter in mind, he was led to a revision not of the model, but of classical physics itself. He based this theory on the results of what was then an independent theoretical branch of physics, namely quantum theory.

In retrospect, we cannot directly connect quantum theory with the inner difficulties of the atomic concepts. Boltzmann appropriately used the following argument in favour of the kinetic theory of heat: a continuous body has many (in the case of strict continuity, infinitely many) degrees of freedom of internal movement. We have seen this to be the case for gases and fluids when we considered turbulence; solid bodies cannot flow but can, however, have internal vibrations of different wave-lengths. All forms of mechanical energy imparted to the body through thrusts, etc. will produce some vibrations of very short wave-length or—in other words—of very high frequency. For the statistical reasons which have already been discussed in the sections dealing with the kinetic theory of heat, this energy will hardly ever return into the very few observable macro-scopic kinds of motion. In other words, mechanics requires disordered movement on a small scale; "if there were no heat, it would have to be invented".

This argument is, however, equally applicable to the interior of finite atoms—and here it turns into an argument against Boltzmann's "billiard ball atoms", for the interior of expanded atoms would also have to vibrate. This, however, would destroy the explanatory value of the kinetic theory of heat. This theory rests precisely on the fact that the energy does not decay into vibrations of ever smaller wave-length, for only then can equilibrium ever be reached, i.e. the condition of equalised temperature and maximum entropy. Atoms, which can get hot by themselves do not explain heat, they simply shift the problem into a different dimension.

This difficulty (which first arose in considering the problem of the rotation of atoms) was not taken very seriously by the supporters of the kinetic theory of the time (with the exception of the most profound of them: J. W. Gibbs) since there was no model of the atom to confront them with it. When, however, statistical considerations were applied in the case of the electro-magnetic field, the laws of which were known since Maxwell's time, the same problem emerged. Just as one asks about the most probable division of energy in a piece of matter, one may also ask what is the most probable distribution of the radiation energy contained in a given space.

Let us think of an empty space with reflecting walls, in which there is nothing but electro-magnetic waves reflected backwards and forwards from the walls. These waves can have many different wave-lengths (and therefore many different frequencies). Every wave of a given frequency and wave-length can be considered as a "degree of freedom" of the radiation field. In the most probable condition, the energy would have to be uniformly distributed over all these different degrees of freedom. Now, however, as one passes to ever smaller wave-lengths, there are ever more degrees of freedom; the radiation field, strictly speaking, has infinitely many degrees of freedom of infinitely small wave-lengths. Therefore no true state of equilibrium could exist. In time, all energy would go into the degree of freedom with very small wave-lengths ("ultra-violet catastrophe").

In fact, however, such an enclosure containing radiation can empirically be brought to a given temperature, for instance by bringing a small, warm body into it, which can

radiate and absorb energy and, therefore, enter into an equilibrium of energy exchange with the radiational field. It then shows a very definite energy distribution over the degrees of freedom: here, above a certain frequency determined by the temperature (i.e. below a given wave-length), there is no longer an equipartition of energy over all degrees of freedom, but a finite amount of energy is distributed over the infinitely many degrees of freedom lying above this limit.

Planck's Quantum

In 1900, Planck explained this discrepancy between experiment and classical physics by the radical assumption of the quantum hypothesis, which we wish to use here in the form of the light quantum hypothesis due to Einstein (1906). When dealing with a vibration of given frequency either in a material body or in a radiation field, it is assumed that this vibration cannot exchange arbitrary amounts of energy, but must exchange either none at all, or a very definite amount which varies as the frequency, or an exact multiple of this amount.

Mathematically speaking, the formula for the quantum of energy corresponding to a given frequency ν is $E=h\nu$. Here h is a new natural constant introduced by Planck, the so-called "quantum of action". How does this assumption help us to an understanding of our problem? For higher frequencies it removes the possibility of the equipartition of energy over all degrees of freedom, since above a given frequency (which depends on the total disposable energy, i.e. on the temperature) a single degree of freedom would, on the average, receive less than its corresponding energy quantum $h\nu$. This however, is not possible according to the quantum hypothesis, unless it absorbs no energy at all. For this reason, there will be hardly any energy at all in all degrees of freedom above this critical frequency, and only in a few will there happen to be a full quantum $h\nu$. The latter will happen the less frequently the higher the frequency, and thus the very high frequencies do not absorb any energy at all, in agreement with experiment. From his hypothesis Planck was further able to derive the quantitative law of the distribution of energy over the frequencies.

Quantum theory can be understood only if one recognises the paradoxical character of its assumptions when considered from the point of view of classical physics. In the latter there is no connection between energy and wave-length. With light quanta (photons) one apparently re-introduces the corpuscular theory of light, despite the fact that the wave theory has been proved by interference phenomena. Let us anticipate historical developments and merely note that in 1924 de Broglie introduced this dualism into matter itself, ascribing a wave nature to the latter—an assumption which was soon proved empirically by observation of interference phenomena with electron beams. From this there resulted a further basic equation. The momentum p of a material particle is inversely proportional to the wave-length λ of the wave associated with the particle: $p=h/\lambda$. Here the factor of proportionality is again Plancks constant h ($6{\cdot}62.10^{-27}$ erg. sec).

Fully conscious of its paradoxical nature, Bohr took over Planck's quantum hypothesis, in order to explain the equally paradoxical fact of the stability of atoms in Rutherford's atomic model. He introduced two postulates:

1. Atoms exist only in sharply defined "stationary states" or "levels", whose energy content differs by fixed amounts; there are no intermediate states.
2. In stationary states the atom radiates no energy at all. Radiation only occurs through transitions between two stationary states. Light is emitted with an energy quantum equal to the energy difference of two stationary levels. The frequency of the emitted light is derived from this energy according to the Planck-Einstein equation $E=h\nu$.

From these assumptions one is able to explain a number of extraordinarily important facts. The stability of chemical atoms is axiomatically contained in them. There is a "ground level" corresponding to the least possible energy content for every atom, in which it cannot radiate at all and is stable for an unlimited time. Apart from this, Bohr was able to derive the spectrum of light radiated by atomic hydrogen: the frequencies of the spectral lines correspond exactly to the calculated energy

differences between the stationary levels. General rules emerge for the interpretation of spectra of all higher elements. The periodic system of the elements was understood in principle (*see* page 135 ff.). By considering the special theory of relativity, Sommerfeld obtained a quantitative interpretation of the fine structure of the hydrogen lines, and thus also one of the most important empirical confirmations of relativity theory.

Quantum Mechanics

In spite of its achievements, Bohr's theory contained many contradictions and nobody knew this better than its author. Its weaknesses remaining from the classical conception were eliminated by a new atomic mechanics which, within its domain of validity, must be considered to be final. This theory was developed through two different approaches: that of Heisenberg (1925) who followed on Bohr, and that of Schrödinger (1926) who followed the Einstein and de Broglie approach. The many successes of this theory of quantum and wave mechanics will be indicated in the following pages. First, however, we must explain the bases of their conceptual structures in so far as this is possible without recourse to formulae.

Let us choose an example connected with the relationship of classical to modern physics (*see* page 85). Let us, for instance, consider a simple structure such as an electron, and for the sake of simplicity let us assume that all those experiments are technically possible for which our assumptions do not contradict any known laws of nature (e.g. quantum mechanics itself). For instance let us assume that the position of this electron could actually be measured by means of a microscope. Note that although this can only be done indirectly and inaccurately today (for instance, by the blackening of the grains of the emulsion on which the electron falls), the direct measurement is not beyond technical possibility. The modern electron microscope can reach down to an order of magnitude of some ten atomic diameters. For our purposes, however, this is sufficient since we are only concerned with finding a very simple representation of the structure of atoms.

Every measurement ends in a sense-datum and thus

leads to a magnitude defined by means of classical physics. For instance, the position of an electron, or its momentum, or its energy, etc., can be measured. Every measurement of this kind gives an "aspect" in the sense that we have already discussed. Now how are these aspects connected? Classical physics can see no problem here at all. For instance, suppose the position and the momentum of an electron at a given moment are measured. If the forces acting on the electron are known, its path can now be calculated and thus all its possible future "aspects" determined.

This, however, can no longer be true in quantum mechanics for the electron has wave properties as well (*see* page 102). These enter in the following way: according to the theory, for any given measurement a certain wave must be associated with the electron. If the momentum is known we could, for instance, say that it is a plane wave or, in other words, one in which points having the same phase lie on a set of parallel planes perpendicular to the path of the particle. Such a wave is spread throughout all space, and its wave-length can be calculated by means of the de Broglie relation. If, however, the position of the electron is known, the associated wave is a "wave packet", i.e. a wave whose amplitude differs from zero only in the close vicinity of the position in which the electron was actually observed. These "wave functions" give the *transformation* to other aspects by means of a probability statement. If we now measure the position of the electron, the probability statement says: the probability of finding the electron in a given place is given by the intensity of the wave function at this place.

The forms of the wave function discussed above show that immediately after a positional measurement there is no probability of finding the electron at any other place; after an exact measurement of momentum, however, the location of the electron is completely undetermined. A simultaneous and exact knowledge of position and momentum would thus ascribe to the wave function contradictory properties, and must therefore, be impossible. In fact, it can be shown that an arrangement for the measurement of one of these two magnitudes precludes the simultaneous measurement of the other magnitude (Heisenberg's uncertainty principle).

Wave theory explains the appearance of the stationary states of the atom; they are comparable with the fundamental and harmonics of stretched strings (*see* Chapter 12).

It is obvious that this theory has basically changed our conception of physical reality. The appearance of probability statements has led to assertions that the causal law has here been broken. The decisive point, however, is not the fact that we can no longer calculate subsequent states from a fully determined original state (this would indeed produce a break in the causal chain), but that at any instant only one aspect of any state can be determined (i.e. either position or momentum), and not the complete state as is required by classical models. What is new is the fact that fundamentally a determination of the state must be referred to the given observational situation at any instant, and that a total separation between the observing subject and the observed object can no longer be made even theoretically. It is a deeper break in the programme of the physics of modern times (as established since Galileo and Newton) than even a failure of the law of causality itself would be.

How deep this breach is will become clear from the question which is occasionally put by philosophers: what is the actual role of the experiment in making an "observation" in the quantum mechanical sense? Is it the physical act of the interaction between measuring apparatus and measured object, or the conscious act of reading the apparatus? It can be shown that both views are false, and that the answer must lie in the factual unity of both acts. An experiment is not made without the co-operation of the human body which interacts with the object by means of the measuring apparatus. Observation is at the same time both this physical inter-relation and an act of consciousness. One will only be able to think of this consistently after a deliberate rejection of the Cartesian division into *res extensa* and *res cogitans* (*see* Introduction).

Elementary Particles (and the means of their observation)

Quantum mechanics may be thought of as a change in classical kinematics. However, it says nothing about the elementary units of which atoms are built and the forces acting between these units.

Particle	*Field*	*Location*	*Stability*	*Mass (electron=1)*	*Charge*
Proton	Nucleon field (*Heisenberg*)	Atomic nucleus	Yes	1840	+
Neutron		Atomic nucleus	Only in the nuclei	1840	0
Electron	Electron field (*Dirac*)	Atomic shell	Yes	1	−
Positron		High frequency and artificial radiation	Only in a vacuum	1	+
Neutrino	Neutrino field (*Pauli*)	β-radiation	?	0	0
Photon	Electro-magnetic field (*Maxwell*)	Everywhere	Only in a vacuum	0	0
Meson (several types)	Meson field (*Yukawa*)	High frequency and Artificial Radiation	No	Several masses above 150	+ − / 0
Gravitational Quantum	Gravitational or Metric field (*Einstein*)	Everywhere	Yes?	0	0

TABLE III: Elementary Particles.

Table III (page 106) gives a survey of what are today known empirically as the "elementary particles". In it every particle is also assigned a field according to the fundamental dualism of quantum mechanics. The relevance of this Table to the structure of the physics of composite bodies has already been discussed in the Introduction. Here we want to see what questions this empirical material poses for realms beyond quantum mechanics.

In modern times the four elements of ancient physics (earth, water, air and fire) have been replaced by a great number of basic chemical elements. When the number of known chemical elements had sufficiently increased, regularities (the "periodic system") were discovered which were finally explained by atomic physics. Similarly, before the discovery of the neutron there were two elementary particles of matter: the proton and the electron. The recent increase in the number of elementary particles makes one hope that one day a common root to all elementary particles and fields may be discovered.

This is borne out by the fact that elementary particles can be changed into one another in many ways: a photon into an electron-position pair, a neutron into a proton and electron, a proton into a neutron and a positron, etc. Further elementary particles (mesons) are produced from the field of force of the atomic nuclei and the kinetic energy of very fast protons.

These transformations take place preferably in the case of very high energies and momenta and accordingly (from the de Broglie relation) of very small wave-lengths. This points in the same direction as certain mathematical difficulties which appear in quantum mechanics in the limiting case of very small lengths. It is assumed that there is a lower limit to our concept of geometrical length.

Single elementary particles, at rest, cannot be experimentally observed. However, the tracks of individual elementary particles and atoms carrying electrical charges can be clearly demonstrated. When charged they can ionise the substance which they have penetrated, i.e. they can tear electrons from the atoms, so that charged atom or molecule remainders (ions) remain.

The first observations of the positions of elementary particles

were made by means of scintillations, i.e. the single flashes on a fluorescent screen which showed that charged elementary particles had hit the latter. This method of observation played a large part in the first investigations of atomic structure by Rutherford and his collaborators.

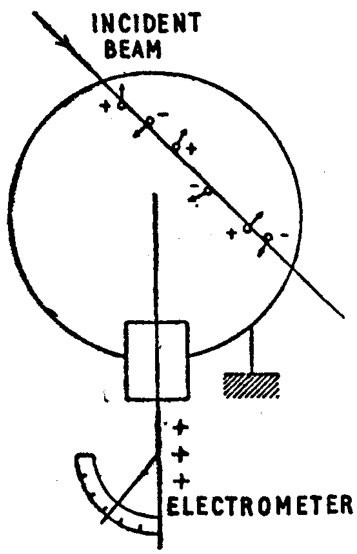

FIG. 14. Ionisation chamber.

In principle, the *ionisation chamber* is a condenser whose plates attract the positive and negative ions or the electrons produced during the passage of an ionising particle. Every time an ionising particle passes through the chamber, a small drop in potential is produced which can be read off from a highly sensitive electrometer. From the magnitude of the drop one can draw conclusions as to the nature of the particle (*see* Fig. 14).

The Geiger Counter

Of great importance in all atomic physics is the Geiger counter (*see* Fig. 15). A thin conducting wire is stretched axially inside a metallic cylinder to which a very high, generally

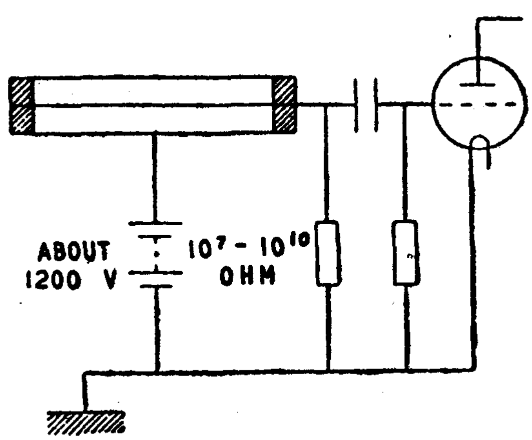

FIG. 15. Counter (with connection to amplifier).

negative, potential is applied. When a charged particle passes through the counter it produces ions and electrons just as in an ionisation chamber. Here the electrons in particular, because of their lightness, are accelerated by the electric field in the

counter, so that they repeatedly ionise the gas inside until finally an "electron avalanche" is produced which builds up within a millionth of a second, and produces a current in the wire. This build-up would lead to a glowing discharge if the latter were not immediately extinguished by means of a very high external resistance. In this manner, passages of the particles produce pulses in the counting wire, which are led to a suitable amplifier and finally can be counted by means of a loud speaker or a mechanical counter.

Uncharged particles, such as light quanta and neutrons which do not ionise directly, can be counted by means of a counter surrounded by a suitable substance in which these

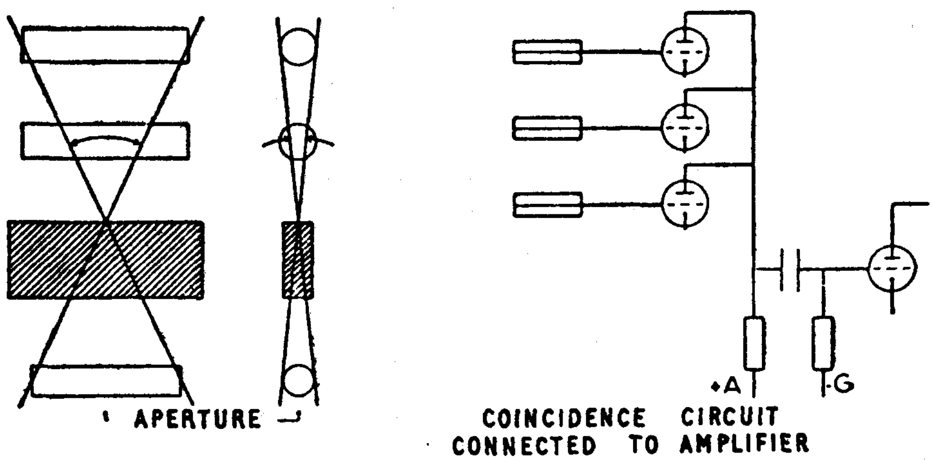

FIG. 16. Coincidence arrangement of counter.

particles produce charged elementary particles to which the counting tube is sensitive. Very energetic radiation, which is not fully braked in passing through a counter but only loses an insignificant fraction of its energy, and which is further not deviated, is capable of passing through a great number of counting tubes in circuit. This enables us to determine the direction of the rays which is particularly important in studying cosmic rays (*see* Chapter 11). A number of counters are placed in a straight line behind one another ("counter telescope") and one now counts the cases in which all the tubes respond simultaneously. If this happens one knows that the charged particle has passed through all of them, and hence its trajectory. By introducing different absorbing materials between the counters one can also determine the energy of the particle (*see* Fig. 16).

The Wilson Cloud Chamber

In the Wilson cloud chamber which is indispensable in modern atomic physics, one can observe the trajectories of single particles and their inter-action with the material through which they have passed (*see* Fig. 17). It contains a gas saturated with vapour (such as water vapour in air) filling the vessel. The vessel is suddenly expanded by rapidly moving the piston forming the bottom of the vessel. The gas expands to the volume of the vessel, and thus the vapour becomes super-saturated. In this condition, it tends to condense into drops. Such drops are most easily formed when ions are present, which can serve as condensation nuclei. If a charged particle has been shot through the chamber just before the

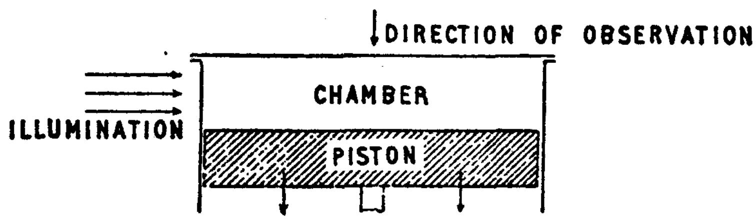

FIG. 17. Cloud chamber.

moment of expansion, the drop formation takes place along its trajectory where the ions have been produced. With side illumination, fine traces of mist can be seen through the upper glass plate against the black background (piston cover), and thus the trajectory of the particle shot through the chamber is made visible (*see* Plate 5). From the density of the track we can draw conclusions as to the nature of the particle. If a strong magnetic field is introduced into the cloud chamber then the trajectories of the particles are deviated according to the velocity of the particles (and to the strength of the magnet) and in a direction depending on the sign of the charge.

As in a cloud chamber the tracks of the charged particles can be investigated on specially designed photographic plates which will show them as a sequence of blackened grains. Recently this method has been used most advantageously for recording rare transformations, especially those due to cosmic rays, and has led to the discovery that there exist more than one kind of meson (Powell).

Chapter 11

ATOMIC NUCLEI AND COSMIC RAYS

BECAUSE of the small size of atoms, direct observation of their structure is as yet impossible, even with the aid of the electron-microscope. We must therefore refer to the indirect manifestations of the atom which can be perceived with the senses, and investigate its structure by means of suitable probes shot into the atom as projectiles. We use projectiles which are themselves of atomic or sub-atomic dimensions, i.e. elementary particles. Naturally, these tiny projectiles cannot be directed individually, but if a great number of them are used, it is probable that some will score a hit. The effects of the hits become visible, for instance, when during the bombardment of a piece of matter, particles are ejected that differ from the bombarding particles, or when the matter becomes radio-active for quite some time. The yield is unfortunately comparable to the result of peppering a big dark railway station with machine gun bullets in order to kill a single fly.

Atomic Projectiles and Structure of the Atomic Nuclei

Our first information on the structure of the atom was obtained by observing the passage of elementary particles through matter: electrons, originating from cathode-ray tubes served as projectiles in the investigations, and Lenard was able to conclude that "the truly impenetrable substance contained in a platinum cube of side one metre is not greater than the head of a pin". Rutherford and his collaborators used positively charged radio-active α-particles, of which we shall speak below, as projectiles and concluded from the scattering produced when they passed through thin sheets of material, that electrostatic forces were acting between the scattering centres and the α-particles. From these results Rutherford concluded that the entire inertial mass of the atoms was contained in a positively charged *nucleus* with a diameter of approximately 10^{-12} cm and around which electrons revolved at a "great" distance (10^{-8} cm).

The chief sources leading to an understanding of the structure of the electron shells of the atom were the spectra of emitted and absorbed light. Light emission and absorption happen in nature constantly, and without human interference. Heat, light and chemical transformation impart to the electron shell an energy of an order of magnitude roughly corresponding to the energy differences between the possible electron orbits in the Bohr model. Thus experiments investigating the atomic shell are directed more towards the analysis and clear representation of the phenomena, than towards their production.

Matters are different in the atomic nucleus. For the transformation of an atomic nucleus energies are needed which are approximately a million times as great as those produced in the atomic shells. Such concentrations are not found under the normal conditions on earth. It is for this reason that atomic nuclei are generally completely unchanged by external influences such as heat, pressure, light and chemical transformation.

The first data on the structure of the atomic nucleus were obtained by means of radio-activity. Some of the elements, especially the heavy ones, have the property of decaying spontaneously without any external energy being imparted to them. They emit either α-particles which prove to be doubly charged positive helium atoms, i.e. nuclei of helium atoms without the two shell electrons, or very fast electrons known as β-rays. Since these particles originate in the nucleus, their emission results in a change of the nuclear charge and—since the chemical properties are determined by the charge on the atomic nucleus—a transformation of one kind of atom into another (transmutation of elements). Together with the emission of α or β particles we can generally observe very energetic electromagnetic radiations, i.e. of very short wave-length according to Planck's relation: the γ-rays. We shall have more to say in the following section about the processes involved in radio-active transformations.

We obtain a more fundamental knowledge of the structure and the construction of the atomic nuclei through the action of projectiles on the atomic nucleus. The first experiments of this kind were made by Rutherford in 1919 at Manchester. He found that protons were produced when nitrogen atoms

were bombarded with α-particles. His investigations showed that the protons, i.e. the hydrogen nuclei, were probably basic units of all atomic nuclei. From experiments some ten years later on the bombardment of beryllium with α-particles, further new particles were discovered, which Chadwick called neutrons. These too, were considered as basic units of the nuclei.

Today we know that every atomic nucleus is, in fact, built up of protons and neutrons. Both particles are approximately of equal weight. The proton (Greek—the first) has a positive electric charge, the neutron is electrically neutral. Both are given the generic name of nucleons.

The number of protons in a nucleus defines, as we have explained on page 100 ff., the chemical nature of the element. However, different numbers of neutrons can be associated with a given number of protons. The number of neutrons can be obtained from the total mass of the atomic nucleus, which is directly proportional to the total number of nucleons apart from correction which we shall soon discuss. In other words, most elements have numerous isotopes: nuclei of different total mass. For instance, apart from ordinary, or light, hydrogen the nucleus of which is simply a proton, there exists heavy hydrogen, the nucleus of which, the deuteron (Greek—the second), contains a neutron as well as a proton. When heavy hydrogen combines with oxygen, "heavy water" is obtained. If the hydrogen nucleus contains two neutrons as well as the proton, we have tritium, hydrogen which is still heavier.

The atomic number (i.e. the number of protons equal to the number of electrons in the atomic shell) is often added to the chemical symbol of the element as a subscript, and the total number of nucleons (which is essentially the atomic weight in chemical calculations) as a superscript: ${}_1H^1$ is an atom of hydrogen with one proton and no neutron; ${}_8O^{16}$ is an atom of oxygen with eight protons and eight neutrons in the atomic nucleus.

Mass Defect

The force keeping the atomic nucleus together is so great that according to Einstein's equivalence relation of energy and mass, it could be weighed. In fact, it makes itself known as a diminution of the mass of the atomic nucleus: the "mass defect". This can be understood as follows: let us consider

that the eight protons and the eight neutrons, which together constitute the nucleus of oxygen, are at a large distance from one another. If we bring them closer, attractive forces come into play, for the nucleus is kept together by such forces. The particles would thus be accelerated towards one another, so that the potential energy of the nuclear forces is changed into kinetic energy. For the particles to stay together, this energy must somehow be given out for instance, as electro-magnetic γ radiation. This amount of energy is now lacking in the atomic nucleus; it is precisely the amount of energy which would have to be supplied to separate it again into its parts. Thus the atomic nucleus must be lighter than the sum of its particles by an amount equivalent to this energy according to Einstein's equation. This mass defect can easily be determined, and is approximately 1 per cent of the mass of the nucleus.

The same defect of mass or energy can also be expressed in electron-volts (eV). One electron-volt is the energy of an electron, or any other particle having one elementary charge, when it is accelerated from rest by a potential of one volt. The energies of chemical reactions produced by changes in the atomic shells are of an order of magnitude of one electron volt, and sometimes (for instance, for many organic compounds) only a fraction of this. The energy, however, with which a single proton or neutron is bound to the nucleus is six to eight million electron volts: in order, therefore, to free the nucleons from the nucleus this same very great amount of energy must be imparted to the latter, and this is best done by means of atomic bombardment.

Radio-active α-particles, the energy of which is of an order of magnitude of five million electron volts, are thus very suitable probes for the investigation of the atomic nucleus. They have the disadvantage that generally only one in about a million particles hits the atomic nucleus. The others are lost in passing through the atomic shells, for they impart their energy to the shell electrons. When the energies are too small, the α-particles cannot come near enough to the nucleus, since they are repelled by the equal charge on the latter.

Protons and deuterons of large energies comparable to those of radio-active α-particles can be produced in gas-discharge tubes with intensities far surpassing that of radio-

active rays. Those hydrogen nuclei contained in the positive (glow) column which have lost their electrons through the discharge are accelerated to the cathode as a result of their positive charge, and are led away through a hole in the cathode (canal rays). They are then further accelerated by a correspondingly high potential, until they possess energies of some million electron volts. In the following section we shall discuss the methods of acceleration separately. While a milligram of radium emits approximately forty million α-particles per second, an artificial proton stream of only one-millionth of an ampere is equivalent to about six billion particles in the same time.

However, α-particles, protons and deuterons can only penetrate and transform the nuclei of light, or at most of medium atoms; the heavy atomic nucleus cannot be reached with them. It was therefore desirable, in the bombardment of nuclei, to make use of the neutrons produced from some nuclear reaction. These, being electrically neutral, can penetrate even the heaviest of nuclei without difficulty. Neutrons of weak intensity can be obtained from nuclear transformations, for instance by bringing beryllium powder into contact with radium in a glass tube. Greater neutron intensities are produced in the "neutron generator" in which, for instance, artificially accelerated deuterons produce neutrons through the bombardment of lithium.

A further possibility of effecting nuclear changes is by means of γ-radiation. For instance, the deuteron can be split into a proton and a neutron by a γ-quantum. Table IV

Bombarding Particles					Particles emitted in the transformation
α	p	d	n	γ	
	+	+	+		α
+		+	+		p
+	+	+		+	n
		+	+		$2n$
	+		+		γ

p=proton, d=deuteron, n=neutron

TABLE IV: Nuclear transformation possibilities.

(page 115) gives a survey of nuclear transformation possibilities, in which the individual basic units of the nucleus remain themselves unchanged.

Particle-Accelerators

To produce elementary particles with an energy of some million electron volts the particles must be accelerated by a correspondingly high potential. This was first achieved in a high-tension apparatus with a Greinacher-circuit. By means of a transformer, there is set up an alternating potential of a few hundred thousand volts, and this is fed by a suitable D.C. transformer to two chains of condensers in series (*see* Fig. 18). The total potential is the sum of the potentials of the single condensers. The potentials so far produced with this arrangement are between one and three million volts.

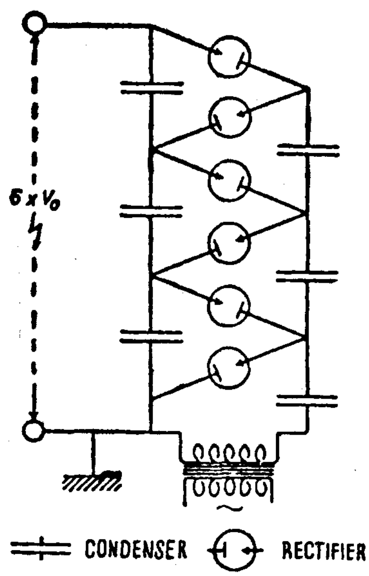

FIG. 18. Circuit diagram of a Greinacher high-tension circuit.

The high-tension generator of van de Graaff (*see* Fig. 19) is based on the principle of the induction machine. Inside a large metal sphere an endless belt of insulating material passes over two pulleys with their axes parallel to each other so that the belt travels in a horizontal plane. A charge is communicated to the belt by spraying positive ions from a D.C. generator. This charge is carried by the belt to the interior of a hollow electrode where a high difference of potential is developed between the electrode and the earth. On principle, this could be increased *ad infinitum*, if an upper limit were not set by the dimensions of the space in which the apparatus is contained. Above a certain potential there will be a spark to the walls and the floor, and thus the conductor will become discharged. Potentials of approximately three to five million volts may be produced with such apparatus.

With high-tension equipment giving potentials of one million to a maximum of five million volts, protons, deuterons and α-particles can be given velocities of an order of magnitude

comparable with the speeds of radio-active rays. Particles accelerated in this high-tension apparatus can therefore interact only with elementary particles and atoms or atomic nuclei, just as is the case with radio-active rays. This procedure, however, has the great advantage that it enables us to investigate the interaction of matter with protons, deuterons and neutrons, i.e. particles that do not occur in natural radio-activity.

It was to be expected from theoretical considerations that particles having an energy of about ten to a hundred times that of radio-active particles would produce very different effects, from those accelerated by means of the Greinacher or van de Graaff apparatus. By means of more strongly accelerated particles it was especially hoped to produce nuclear fission and fragmentation, and also artificial mesons which had previously only been observed in high frequency radiation.

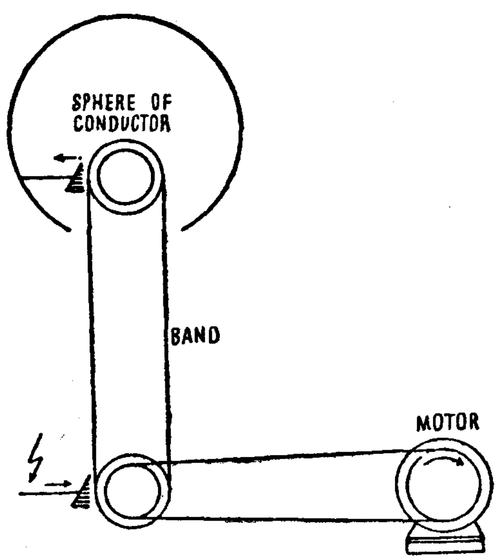

FIG. 19. Electrostatic high-tension generator (van de Graaff).

The Cyclotron

The most important apparatus for the acceleration of particles to higher energies is the cyclotron, in which the particles are exposed to numerous successive, moderate potentials, and are thus brought to velocities corresponding to particle energies of some hundred million electron volts. In this, use is made of the fact that a charged particle moving in a constant magnetic field has a circular orbit due to the lateral force of the magnetic field: the greater the circle, the faster the particle. The time that the particle takes for one revolution does not depend on its velocity. A fast particle describes a large circle in the same time that a slow particle describes a smaller circle. The period of revolution is determined only by the strength of the magnetic field and by the electric charge of the particle.

If we now combine the magnetic field, which always brings the particle back to the same place after the same period of time, with an alternating electric field, the latter will always accelerate the particles in the same direction at the end of each revolution. This is used technically in the following manner: the accelerated particles are formed or introduced between two flat, semi-circular containers, the "dees" (*see* Fig. 20). The plane sections of the dees facing each other carry two electrodes to which a high frequency alternating potential is applied, by means of a strong short-wave transmitter with a peak potential of about 30,000 to 100,000 volts, and a frequency of about ten

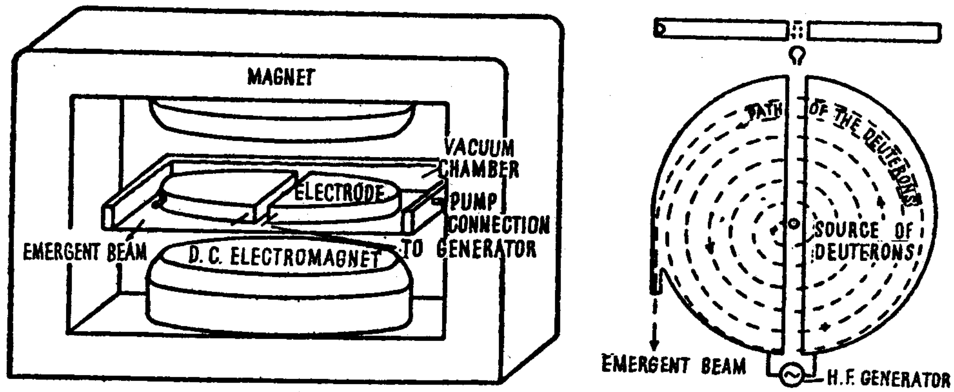

FIG. 20. Construction of the cyclotron.

million oscillations per second. The dees are placed in a very strong constant magnetic field. Each half period, the charged particles are pulled into one of the containers, the trajectory inside which is a semi-circle on account of the applied magnetic field.

The frequency of the applied alternating field is chosen so that the particles, after describing one semi-circle, enter into precisely the opposite field at the slit between the two dees, and are thus accelerated still further in the opposite direction. Corresponding to its now greater energy, the particle describes a larger circle in the unchanged magnetic field in the same time. When the particle returns to the slit once more, it again finds an accelerating field, because of the chosen frequency of the alternating field. This process is repeated a few hundred times in the cyclotron so that the trajectory of the particles is made up of orbits of ever-increasing diameters, so forming a spiral of several hundred turns. At the edge of the container the beam of particles is displaced by an additional electrical field and

directed wherever we wish to work with it. In large cyclotrons it is possible to produce particles with an energy of up to some hundred million electron volts.

The velocities of particles with these great energies are already a significant fraction of the velocity of light, so that the relativistic dependence of the mass of the particles on their velocity is appreciable. With increasing particle mass, however, the increase in velocity due to the electric field becomes less than would be the case with a fixed particle mass, so that at these great velocities the particles would no longer pass between the electrodes in phase with the alternating field, but would become irregularly dispersed, and the arrangement would cease to function. Thus an upper limit is set to the possible particle energies produced in cyclotrons. This limit, however, can be extended by lowering the applied frequency for the external trajectories to compensate the increase in mass. This is done in the synchro-cyclotron by making use of frequency modulation.

By means of the cyclotron, protons, deuterons and α-particles can be accelerated. The acceleration of electrons cannot be satisfactorily carried out in the cyclotron. Since the electrons have a very small mass, the accelerating field would impart to them so great a velocity that the frequency would have to be far greater than for the acceleration of the other elementary particles and an adequate increase of the frequency would be technically very difficult even today. Furthermore, the mass of the electrons is considerably increased since their velocity would approach that of light, so that the effects mentioned above apply to the electrons particularly, and the accelerating action of cyclotrons on electrons would normally cease, even at relatively small particle energies.

The Betatron

In the betatron (*see* Fig. 21), which is also called the electron-catapult, electrons can be brought to energies as great as those of heavy particles accelerated in the cyclotron. The principle on which the betatron works is the formation of a circular electric field in a magnetic field changing with time. This principle is also used in the case of the transformer. The electrons move in a tube replacing the transformer winding, and

in one revolution they will be accelerated by an electrical potential equivalent to the voltage, that would be produced in the winding of the secondary spool of a transformer. On account of the increasing velocity of the particles a constantly increasing magnetic field is required to maintain the required circular motion in the tube. This is provided precisely by the increasing magnetic field that produces the accelerating electrical potential.

An acceleration of electrons up to energies of some hundred million electron volts can also be produced in the synchrotron, which apparatus is a combination of the cyclotron and the betatron. Just as in the case of the cyclotron, the acceleration of the particles is produced between two electrodes. The particles

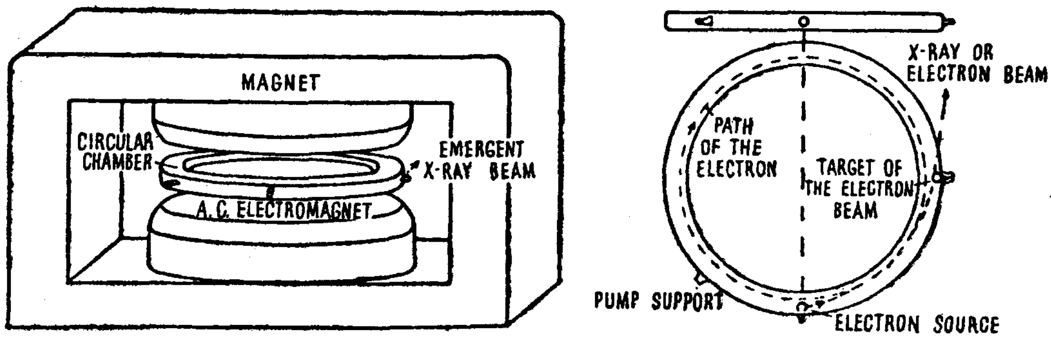

FIG. 21. The principles of the construction of the betatron.

are kept on the same fixed orbits by means of a magnetic field increasing with time and corresponding to their increase in velocity.

The linear accelerator works without a magnetic field. Pre-accelerated particles (electrons and heavy particles) enter a tube some meters long, in which they are exposed to accelerating electric fields which act upon a particle just at that instant at which it enters the position of action. Technically this effect is produced by means of a travelling electric wave which, in practice, runs with the particle and always produces an electrical field at the position of the particle in such a way that the particle is constantly accelerated.

Nuclear Transformations

We must now pose the question of the origin of nuclear forces. This we can only do in a roundabout way namely, by talking about the transformations of atomic nuclei. We can

distinguish two types of transformation: those in which the individual nucleons do not change (normal fragmentation, demolition and building-up processes; α-decay) and those in which the nucleons themselves are transformed (β-transformations). We have already spoken of the first type. Here we are concerned with the second.

The basic process in the β-transformation is the transformation either of a proton into a neutron or of a neutron into a proton, with the simultaneous production or destruction of lighter particles. The "visible" result of the transformation of a neutron into a proton is an electron (the proton-electron combination is electrically neutral) and of the converse transformation is a positron (or the disappearance of an electron). The latter, however, does not occur in the case of natural radioactivity, but is only produced by the artificial bombardment of atomic nuclei with elementary particles (artificial radioactivity). Whether an electron or a positron will appear depends on the energy relations. For instance, oxygen has five known isotopes of atomic number 15, 16, 17, 18 and 19. The eight protons are associated with seven neutrons in the lightest isotope, and with eleven in the heaviest. The three middle isotopes are stable, and the remaining two, which were only produced artificially by means of transformation processes, are unstable. The lightest isotope is transformed spontaneously (it is an artificial radioactive source) by means of a β-process from ${}_8O^{15}$ to ${}_7N^{15}$, i.e. it changes one of its protons into a neutron; similarly the heaviest isotope changes from ${}_8O^{19}$ to ${}_9F^{19}$ by the transformation of one of its neutrons into a proton. The binding energy of the nucleus is greatest when protons and neutrons are in a certain ratio (close to 1 : 1). Every nucleus that deviates too far from this ratio will spontaneously change nucleons of the most frequent sort into those of the rarer until the optimal ratio is reached.

Actually the β-process is a little more complicated than we have just described it. According to Pauli we must assume that together with an electron or positron, there is always produced a neutrino, a light neutral particle which cannot be observed directly. This is a requirement of the laws of the conservation of energy and of linear and angular momentum. According to Yukawa we must further assume that the first product of the transformation is neither an electron nor a neutrino, but a

previously unknown particle, the meson. The meson, however, is unstable and is soon changed into an electron or a neutrino.

What is the relevance of all this to the problem of nuclear forces? For purposes of comparison let us consider the atomic shell. It is held together by electrical forces. However, its internal electro-magnetic field can occasionally produce external effects, for instance when the atom emits light. This light, considered from the point of view of the field, is an electromagnetic wave; it is perceived in its particle-aspect as a photon. Before its emission the photon was not a component of the atom, it has been "newly created" during the emission. What was present previously was only the energy in the electrical field of the force keeping the atomic shell together.

In the case of the atomic nucleus also, we can see particles emerge: electrons or, according to Yukawa, mesons which are not components of the nucleus. We interpret this in the following manner: inside the nucleus there is a field, the meson field, which binds the nucleons to each other. As a result of internal changes, its energy can partially flow to the outside as a meson wave. The particle corresponding to this wave is the meson. However, mesons are not known well enough, and the theory of nuclear forces is therefore still too problematical to be considered as well-established as that of the atomic shell.

Nuclear Fission

Radar and the atom bomb are results of modern physics which have made world history. We shall only consider the physical background to the technical exploitation of atomic energy. The popular name "atomic energy" means nuclear energy which has been known for long. Its technical exploitation, however, had appeared as impossible for decades. Atomic nuclei either did not give up their energy at all, or only in the case of radio-activity at a rate much too slow for human purposes. Because of the meagre yield, nuclear transformations brought about by bombardment with charged particles could never lead to a technical exploitation. Neutrons, which alone can penetrate the nucleus freely, could at that time only be obtained through nuclear bombardment by charged particles so that the loss factor of 1 : 1,000,000 valid for charged

particles, still held in the case of neutrons, because of the way in which they were produced.

Physicists knew this and did not even search for a means of releasing nuclear energy. Pure research led accidentally to a discovery which changed this state of affairs. In December 1938 Hahn and Strasmann discovered that neutrons could split the heaviest nuclei (especially of uranium) into two parts of comparable size. When this happens the amount of energy liberated is not determined by the neutrons but is already previously contained in the nucleus; the latter is analogous to a tightly wound spring which the neutrons bring to a sudden release. The "potential" is of electrical nature. The great number of protons in these heavy nuclei repel one another electrically. They are held together by nuclear forces, but when the nucleus is brought into internal oscillations (even of the weak kind caused by the neutron), this disturbance can lead to a state of disequilibrium, and the nucleus will split into two.

After the publication of these discoveries and after testing them in many laboratories throughout the world, many physicists found independently that during this splitting, some neutrons were liberated just "by the way". This opened up the possibility of a *chain reaction.* A neutron can split the uranium nucleus and simultaneously produce more neutrons; these may strike further uranium nuclei and so produce further neutrons, and this process continues until all the uranium has been used up or evaporated, or until the process is stopped by the increasing pollution of the uranium due to the products of the reaction which partially absorb neutrons. If this reaction takes place slowly we have a heat-producing apparatus ("uranium reactor" or "pile"), and if it takes place quickly a bomb. Which of these two happens depends on the procedures adopted. (*See* Figs. 22 and 23.)

There are two isotopes of uranium: ${}_{92}U^{235}$ and ${}_{92}U^{238}$. The first can be split by neutrons of any velocity; in fact this is best done with very slow neutrons, which can remain in the vicinity of the same nucleus for long periods, and are therefore able to react with it "at leisure". ${}_{92}U^{238}$ can absorb neutrons below a fixed velocity without fission taking place. Under the influence of these absorbed neutrons, and by means of subsequent β-processes it changes into an element not found in

nature, i.e. plutonium ($_{94}P^{239}$) which also has the same fissionable properties as U^{235}. In natural uranium only 1/140 of the total material is U^{235}, the rest is U^{238}.

If we use natural uranium, all neutrons, with the exception of the very slowest, are absorbed by the U^{238}. The chain

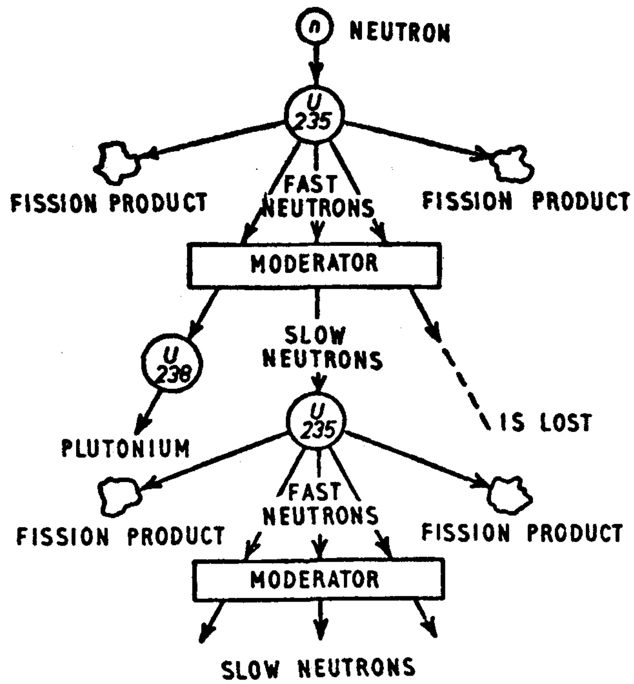

FIG. 22. Chain reaction in the uranium pile.

reaction can then only take place if the uranium is brought into contact with a "moderator", to slow down the neutrons which acquire a considerable velocity as the result of fission. The nuclei of the light atoms are eminently suited to this purpose, for the neutrons colliding with them can impart a considerable part of their velocity to them during each collision. On the other hand, the moderator itself must not absorb neutrons. Both conditions are satisfied mainly in two substances: heavy water and pure carbon. Both substances have been used in practice.

The reaction with natural uranium and slow neutrons is suitable for the uranium pile. Whether a suitable combination of uranium cubes or bars with a moderator does in fact produce heat, depends further on the quantity of the substance used.

Too small a quantity does not "burn", just as a small piece of coal does not burn. This is due to the fact that neutrons can be lost during the reaction by escaping through the surface of the pile into the surrounding space. Every neutron has to travel some centimeters on the average before hitting a uranium nucleus; if it reaches the surface before going this distance it is lost to the chain reaction. For this reason, even the smallest piles, those with heavy water, must contain hundreds of kilograms of uranium, and the carbon reactors are as large as a house.

A pile of the necessary magnitude starts working spontaneously, for there are always a few neutrons rushing about in every substance, because of the nuclear destruction caused by cosmic rays. Furthermore the size of the pile regulates the temperature; for with increasing temperature the yield of the chain reaction decreases. At a certain temperature so many neutrons will escape from the surface that any further heating would stop the reaction and would therefore lead to cooling. Thus the pile is a heat reservoir at a temperature determined by its construction and which, as long as the supply of U^{235} suffices, does not cool even when heat is being removed.

The peaceful technical exploitation of the uranium pile as a source of energy has only just begun, since many technical problems have still to be solved. We may assume that it will contribute a considerable amount to the energy economy of the earth. However, a natural limit to this exploitation is set by the quantities of uranium at our disposal. There is a far greater amount of coal on earth than uranium, but uranium may represent a somewhat larger supply in terms of energy. The problem of energy-waste, which humanity will probably tackle only when it is too late, is thus not yet solved with atomic energy.

Some very important products of the uranium pile are radiation of great intensity (especially neutron radiation) and above all, the radio-active elements created in its interior. During the fission of uranium a great number of radioactive elements are produced. These can be used as indicators in chemistry and medicine and also therapeutically (*see* page 144).

The atom bomb requires that the substance to be split

must be pure. For this purpose U^{235} is separated from U^{238} in great quantities, or alternatively the plutonium produced in the uranium pile is extracted chemically (*see* Fig. 23). Both procedures require a tremendous technical effort. For instance, one method of separating the isotopes (which of course do not differ chemically) is making gaseous uranium in quantities of many tons diffuse again and again through porous walls. During one passage through the wall, the proportion of the isotopes may change from 1:140 to 1:137 since the lighter

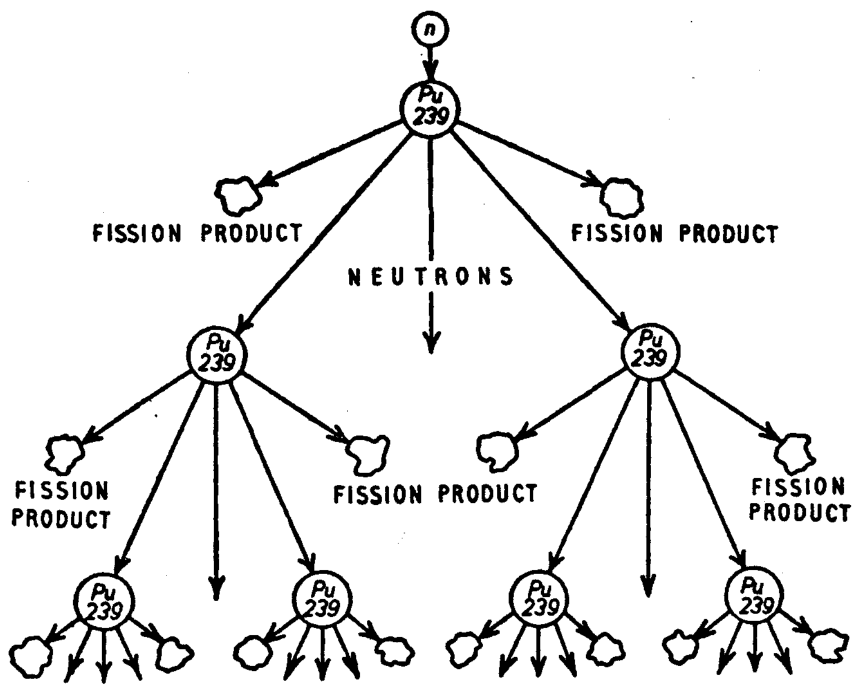

FIG. 23. Explosive chain reaction in the atom bomb.

isotope is more mobile. This process is repeated until only the initially rare isotope remains. Perhaps the historical comment may still be relevant that because of this difficulty, a German atom bomb was quite impossible during the Second World War. German physicists were relieved of the decision whether they wanted to make atom bombs or not: recognising the tremendous effort required, they could not even contemplate building an atom bomb. The technical requirements for such an undertaking, in the course of a war, were only present in America, and even there remarkable technical efforts were necessary.

In the bomb too, the chain reaction only takes place starting from a critical mass of substance. Smaller quantities

of U^{235}, or plutonium are completely harmless. Thus, the explosion is produced only through the sudden contact of previously separated quantities of substance, so that the critical mass is exceeded.

While in the Uranium bomb heavy nuclei are split, in the Hydrogen bomb light nuclei are built up to form heavier ones. Thus heavy Hydrogen is transformed into Helium. The process bears some resemblance to that supplying the energy of the sun.

Cosmic Rays

The greatest concentration of energy known for individual particles is found in high energy radiation from the cosmos, i.e. cosmic rays. It can be observed experimentally mainly by means of the ionisation of air, in counting tubes and ionisation chambers, and by means of ionisation tracks on photographic plates placed in the Wilson cloud chamber. The phenomenon is very complex; today we have roughly the following picture of it: atomic nuclei and especially protons, enter the atmosphere with a very high energy. The average energy of one of these primary particles is almost 10^{10} eV (compare this to the binding energy in the nucleus which is hardly 10^7 eV). Single particles have energies up to 10^{16} eV. This means that the velocity of the particle is almost that of the velocity of light. It must be stressed, however, that no technical application of these energies is to be expected, if only because of the scarcity of the rays, though the total energy from this high energy radiation constantly reaching the earth is approximately as great as the total energy of the light reaching us from the stars at night.

The origin of these particles has not yet been explained. In the last few years opinion has swung in favour of theories that place their origin in electro-magnetic processes either in the stars such as the sun, or in interstellar space. We know that in terrestrial thunder storms electro-magnetic fields of large spatial dimensions are occasionally produced, and that they can strongly accelerate small quantities of charged matter; potentials of up to 10^9 volts can occur during lightning.

The penetrating primary particles hit the atomic nuclei of the atmosphere and as a result of collisions, they apparently

form mesons. This is to be expected if the nuclear field of force is a meson field, since electrically charged particles in colliding with one another produce electro-magnetic radiation, just as every mechanical collision gives rise to sound waves. The mesons would then be the "noise" which these nuclear particles produce during the collision. In any case, mesons which were originally postulated purely theoretically by Yukawa from nuclear physics, have been found empirically in cosmic rays.

The mesons are not stable but change spontaneously within a millionth of a second, first into other kinds of mesons and finally into electrons. The latter may then give rise to a cascade process: an electron passing near an atomic nucleus will also occasionally produce a "noise", i.e. a light quantum carrying away a considerable fraction of energy. Such a light quantum will in turn, when colliding with a nucleus, change its energy into an electron and a positron. This process (pair creation) is one in which matter is created from light. The electron and the positron in their turn will again create new light quanta. Thus the number of particles is multiplied in a cascade until the energy has been used up. Large cascades may contain thousands of particles (*see* Fig. 24).

The main interest of cosmic radiation lies in the fact that in it we can observe the behaviour of matter with very great energies. It has already led to the discovery of many elementary particles (the positron and many types of meson). Work in this field is still in full swing.

Astrophysics

Ever since the calculation of the proper motions of the planets had proved the correctness of Newton's laws, astronomy has been a field in which new physical knowledge can be applied. Atomic physics is following in this tradition.

Atomic physics was first applied in astronomy to the study of the surfaces of luminous stars. What we know of these stars is essentially the spectrum of the light they emit. Immediately upon the discovery of spectral analysis, Kirchhoff and Bunsen concluded that heavenly bodies consist of the same chemical elements as the earth since they showed the same spectral lines as the latter. From observations of the strength and breadth of spectral lines and from the atomic theory of

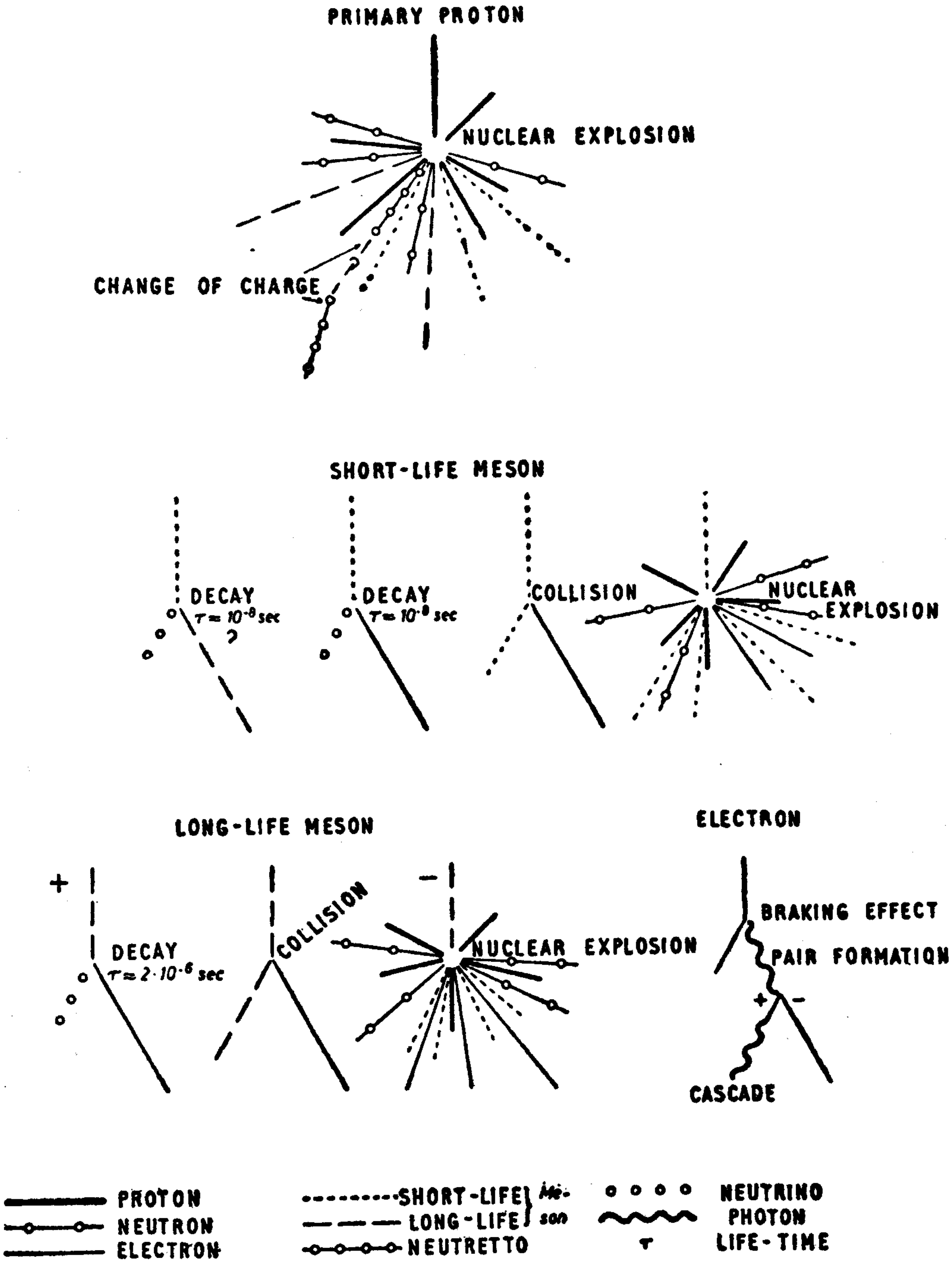

FIG. 24. Scheme of the (probable) interactions of cosmic radiation.

their origin, we can nowadays deduce the temperature of the stellar surfaces (which, according to type, are between 3,000° and 50,000° or more), the frequency with which individual elements are present, the density of gases, the velocity and rotation of the stars, and many other facts. Naturally the investigation of our sun has progressed further than any other investigation of this kind.

Matter distributed between the stars in space manifests itself also through spectral lines. Today we know that it is comparable in quantity to the matter concentrated in the stars, and we have begun to understand the laws governing its motion.

Purely theoretical conclusions, due mainly to the work of Eddington, have led to the theory of the structure of the stellar interior. Atomic physics enables us to calculate the behaviour of matter, for instance in the interior of our own sun, so accurately that theoretical derivations of the quantity of energy constantly radiated by our sun are in very good agreement with experiment. The source of this energy is to be found in atomic nuclear processes. Stars, however, obtain their energy not through the fission of heavy nuclei, as happens in nuclear technology on earth, but through a building-up of the lightest nuclei, similar to the Hydrogen bomb. Hydrogen is built up into helium, with carbon acting as a catalyst.

The application of atomic physics to the question of the history of the cosmos, in general, will not be considered more closely here, because it must be considered as still being too hypothetical.

Chapter 12

THE STRUCTURE OF MATTER

OUR line of approach so far has gone from the more known to the less known, from the visible to the hidden, from the extended body to the elementary particles. Atomic physics, if correct, should enable us to reverse the problem. How, if we assume the presence of elementary particles, can we explain the properties of extended bodies? We should now be able to deduce from atomic physics the great number of empirical facts which emerged from our study of chemistry and of classical physics, and which paved the way for our inductive advances in atomic physics.

We may truly say that this was achieved twenty-five years ago with the postulation of quantum mechanics. Because of the mathematical complications involved, however, we cannot go beyond a certain point. All the same, atomic physics is mathematically simpler than classical physics. Stellar mechanics has been able to solve the problem of the motion of three bodies under the influence of their mutual forces, for instance a binary star and a planet, only by labours taking decades and involving an extraordinary effort of calculation, and then in special cases only. In quantum mechanics the corresponding problem (helium atom: one nucleus and two electrons; hydrogen molecule: two nuclei and one electron) was solved in a shorter time than could have been expected, and the calculations were tested empirically; theory and observation agree up to the eighth decimal point. However, larger bodies, even heavy atoms, contain such a great number of elementary particles that the total relationships are beyond all human calculation.

In these cases we can only hope to deduce general rules. Thus we do not wish to deduce the properties of every single chemical compound but the basic ideas and laws of chemistry such as valency, structural formulae, etc.; just as we do not calculate the electric resistance of complicated alloys, but

deduce Ohm's law and the difference between conductors and insulators from other properties of the materials. This has been done to a point where hardly a single fundamental property of inorganic matter has remained unexplained.

Let us illustrate this process of deduction at least by means of a few examples. We can distinguish three stages in the construction of matter: the single atom, the molecule composed of atoms, and the condensed body (liquid or crystal).

We have already spoken of the single atom. However, we paid little attention to those properties of the atom which produce the perceptible differences in the elements: the spectral lines of the light emitted by the atom of an element and its

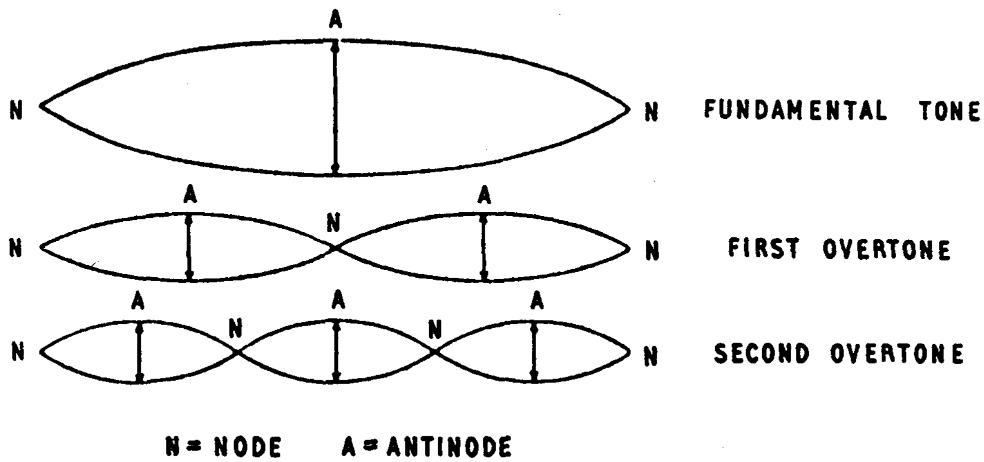

FIG. 25. Vibration of strings.

place in the periodic system of the elements. Both were first interpreted simultaneously by Bohr. Now, the periodic system of the elements is a tabulation of empirical chemical data, i.e. of data that deal with the aggregation of atoms into molecules. Thus we can see that in certain respects the first two of the above-mentioned stages must be treated simultaneously. The single atoms reveal certain properties only in their interactions with other atoms.

The spectra and chemical properties of the atoms depend on the structural possibilities allowed for the shell electrons. Let us, as the simplest example, consider the hydrogen atom. A stationary state can be characterised by the number of nodes in the wave-picture. These concepts may be understood if we make comparisons with a vibrating string (*see* Fig. 25). The fundamental note corresponds to a vibration with only a single

bulge. The first overtone (an octave above the fundamental note) has a node in the middle of the string, where the string is at rest. In the second overtone (a fifth above the first overtones) there are two positions of rest and so two nodes, etc. Thus we can enumerate the overtones according to nodes.

The vibration of the electronic wave which spreads three-dimensionally in space is at rest in nodal surfaces. The ground level has no node at all, just as in the case of the string. The first excited state has one nodal surface. This can be orientated in different ways in space; it can be shown that there are four basically different forms of vibration of the electron wave with exactly one node. The nodal surface is either a spherical surface centred on the atomic nucleus, or a plane through the position of the latter. In the last case the three mutually perpendicular planes which can be constructed at any point in space are considered as basically different (the one separates above and below, the other right and left, the third front and back). The spherical surface must be added as a fourth surface. The second excited level has two nodal surfaces: either two concentric spheres, or one sphere and one plane, or two planes. It can easily be calculated that in this case there are nine different states of vibration. The third excited level has sixteen possible states for three nodal surfaces, etc.

Now, the hydrogen atom contains only one electron usually in the ground state, which, however, can pass into one of the excited states if the necessary energy is imparted to it. If the energy is given to it in the form of light, the electron will absorb a certain energy quantum which is determined exactly by the energy difference of the two states, and to which, according to the Planck-Einstein relation there corresponds a certain frequency of light. For this reason atomic hydrogen only absorbs certain frequencies, and thus produces only certain dark lines in the spectrum (the Balmer lines). The excited atom can emit these very frequencies by passing into one of the lower states (*see* Figs. 26 and 27).

In the heavier atoms similar processes are possible. However, here there is more than one electron, and an additional law of quantum mechanics enters—Pauli's exclusion principle. It states that no two electrons can be in the same state; but the state of the electrons is to be characterised not only by the

nodal surfaces of the wave function, but also by a further magnitude, the spin, which can assume two distinct and different values. The theory of spin is too far beyond the framework of a pictorial representation for us to enter into it more thoroughly.

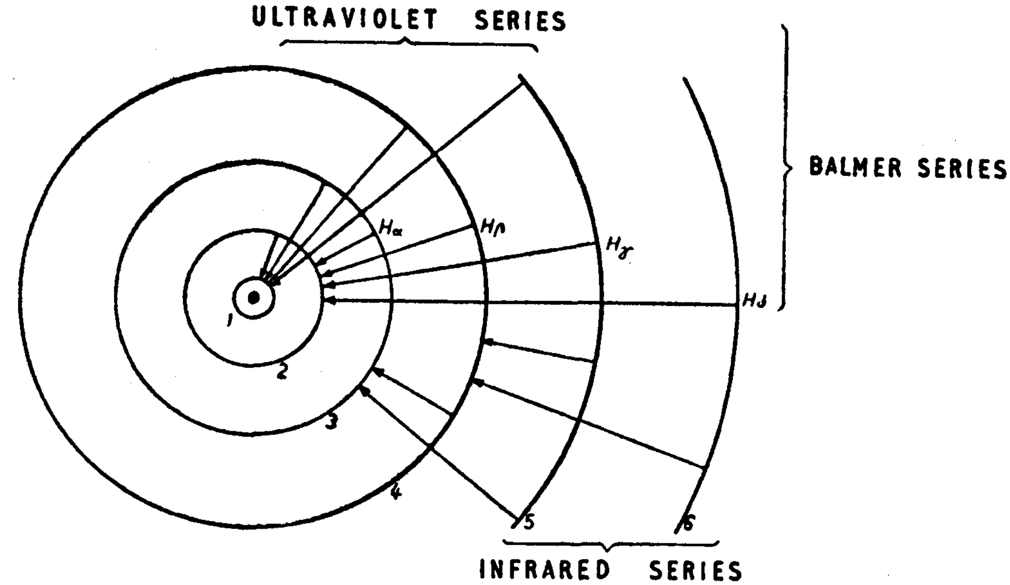

FIG. 26. Schematic representation of electron transitions in the atomic shell.

Let it suffice that because of the spin, there are precisely two electrons each of which have the same characteristic function. For this reason the ground level can be occupied by two electrons, the first excited level by eight electrons, the second by eighteen electrons, etc. This scheme must be modified further,

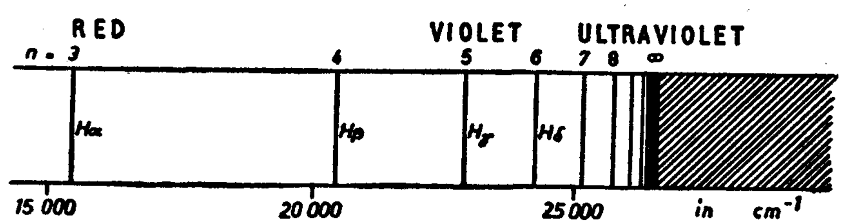

FIG. 27. The Balmer series as a spectrum.

since the presence of other electrons changes the wave function of one electron; this for instance produces a "splitting" of the second excited level into eight wave functions which are occupied preferentially before the ten remaining ones.

If we now follow the sequence of chemical elements from hydrogen to the heaviest elements we shall find that every time the electron number is just sufficient to fill one level completely,

the element concerned will have the chemical character of one of the inert gases. Thus, helium has precisely two electrons, neon 10 (i.e. 2+8), argon 18 (2+8+8; the second excited level is only completed as far as the preferentially occupied wave functions), etc. Thus these "closed shells" are evidently self-balanced structures which make the removal or the addition of further electrons very difficult. The atoms of the inert gases are completely inert towards one another and to their neighbours in the periodic table and neither give electrons to them, nor take them away. Now, chemical bonds always presuppose a certain electron exchange between the atoms united into one molecule. Thus the inert gases do not react chemically and can only be condensed at very low temperatures. Helium has the lowest known boiling point of approximately 4°K.

The Periodic Table

This simple consideration alone shows how the periodic recurrence of certain chemical properties with increasing atomic numbers, as shown in the periodic system (*see* Table V), has come about. We can make this clear by an example. The last element before an inert gas, i.e. one which has just one electron less than the inert gas, is always a halogen (fluorine, chlorine, bromine, iodine). It easily combines with an alkali (lithium, sodium, potassium, etc.) to form a salt. The alkalis follow immediately upon the inert gases, and have just one electron more than the preceding inert gas. It has been found that in a salt (for instance, kitchen salt NaCl) the alkali is electrically positive, while the halogen is electrically negative. In this case the chemical bond is the consequence of the electric attraction of both atoms. This electric charge is produced by the tendency to form closed shells.

If the alkali metal gives up one electron, and if the halogen takes it up, then for each we obtain precisely the closed shell of the inert gas. In that case it would be just as saturated towards the environment as the inert gas itself; however the halogen will have one electron more than corresponds to its nuclear charge and will thus be negative, while the alkali will be one electron short and thus be positively charged. It is these two charges that attract each other.

This kind of chemical bond is called "heteropolar".

Period	I	II	III	IV	V	VI	VII	VIII
1	1 H 1·0080							2 He 4·003
2	3 Li 6·94	4 Be 9·02	5 B 10·82	6 C 12·01	7 N 14·008	8 O 16·0000	9 F 19·00	10 Ne 20·18
3	11 Na 22·997	12 Mg 24·32	13 Al 26·97	14 Si 28·06	15 P 30·97	16 S 32·06	17 Cl 35·457	18 A 39·94
4	19 K 39·096 29 Cu 63·57	20 Ca 40·08 30 Zn 65·38	21 Sc 45·10 31 Ga 69·72	22 Ti 47·90 32 Ge 72·60	23 V 50·95 33 As 74·91	24 Cr 52·01 34 Se 78·96	25 Mn 54·93 35 Br 79·916	26 Fe 27 Co 28 Ni 55·85 58·94 58·69 36 Kr 83·7
5	37 Rb 85·48 47 Ag 107·880	38 Sr 87·63 48 Cd 112·41	39 Y 88·93 49 In 114·8	40 Zr 91·22 50 Sn 118·70	41 Nb 92·9 51 Sb 121·76	42 Mo 96·0 52 Te 127·6	43 Tc 53 I 126·92	44 Ru 45 Rh 46 Pd 101·7 102·9 106·7 54 X 131·3
6	55 Cs 132·91 79 Au 197·2	56 Ba 137·36 80 Hg 200·61	57 La* 138·90 81 Tl 204·39	72 Hf 178·6 82 Pb 207·21	73 Ta 180·9 83 Bi 209·00	74 W 183·9 84 Po 210	75 Re 186·31 85 At	76 Os 77 Ir 78 Pt 190·2 193·1 195·23 86 Em 222
7	87 Fr	88 Ra 226·05	89 Ac ~227	90 Th 232·12	91 Pa ~231	92 U† 238·07		

*Between 57 La and 72 Hf: "rare earths"

58 Ce	59 Pr	60 Nd	61	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	17 Cp
140·13	140·92	144·27		150·43	152·0	156·9	159·2	162·46	163·5	167·2	169·4	173·0	175·0

† Trans-Uranium Elements: 93 Neptunium (Np), 94 Plutonium (Pu), 95 Americium (Am), 96 Curium (Cm), 97 Berkelium (Bk), 98 Californium (Cf).

TABLE V: Periodic System of the Elements. (The atomic numbers, chemical symbols and mean atomic weights are given.)

"Homopolar" bonds are those between two equal or similar atoms, as for instance in the hydrogen molecule consisting of two hydrogen atoms. Here the two electrons both revolve around both nuclei. If heavier atoms are homopolarly bonded, for instance two oxygen atoms, then electrons that are near the nucleus remain the property of each atom, while the outer electrons are common to both atoms and cause the chemical bond. The "valency line", connecting two atoms in the structural formula, is physically speaking, a pair of electrons common to both atoms. A double bond (two valency lines between the two atoms) corresponds to four common electrons.

By means of these ideas the structure of simple molecules has been brought into good quantitative agreement with chemical experiments.

The Structure of Liquids and of Solids

Roughly speaking, a solid differs from a liquid in that it has a regular array of atoms. Solid bodies in this strict sense of the word are always crystals. It is true that most of them are not

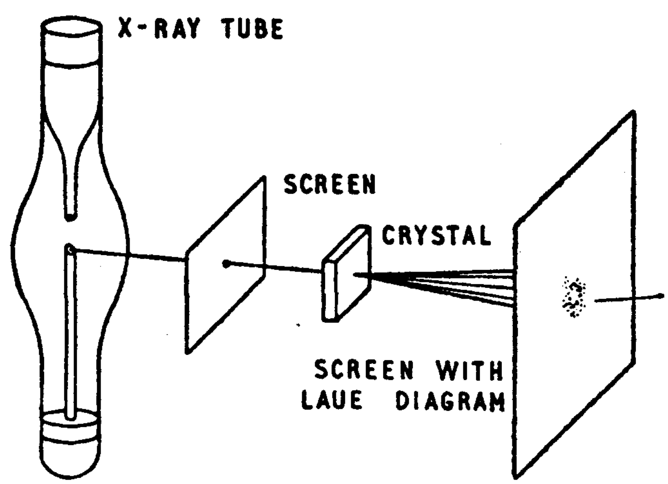

FIG. 28. Arrangement in the production of X-ray interference.

monocrystals, i.e. large, uniform pieces whose regularity can be seen with the naked eye. Rather do they consist of many microscopically small crystals, which in their turn are placed irregularly with respect to one another (most metals are like this).

The regularity of the arrangement of atoms in the crystal can be proved by an experiment designed by von Laue, in which X-ray interference in crystals is produced (*see* Figs. 28–30).

J

We know that light falling on a grating, made up of regular, fine slits placed next to one another on a plane glass, is displaced in very definite privileged directions, the directions of the diffraction maxima (*see* page 39) provided that the distance between two neighbouring slits is of the same order of magnitude as the wave-length. Now the wave-lengths of X-rays are approximately as large as the distances of the atoms in the condensed body. If these atoms are regularly ordered, then interference phenomena, characteristic of the particular order, will be noticed. We can deduce that the order of atoms in the crystals, which can be likened to a three-dimensional grating, only admits of diffraction maxima for certain wave-lengths in a very definite direction.

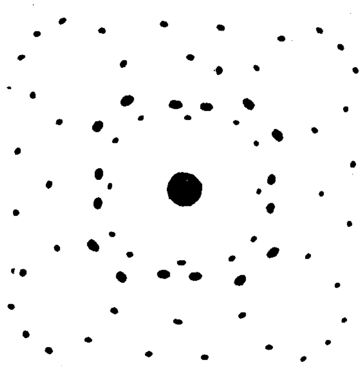

FIG. 29. Interference in a crystal of zincblende.

On a photographic plate perpendicular to the direction of the primary X-ray beams, and behind the transluminated crystal, these diffraction maxima appear as dark points, the aggregate of which represents the "Laue diagram". The intensity of its darkening is essentially influenced by the type of atoms of the grating. From the corresponding position and symmetry of the points in the Laue diagram, the order of the atoms in the crystals can be unequivocally determined. Conversely, if the crystal structure is known, the position of the diffraction maxima can be used for the determination of X-ray wave-lengths (X-ray spectroscopy).

Investigations of the structure of crystals have a special technological significance for the determinations of the fine structure of materials. If the substance to be investigated contains more than one component, as is the case in alloys, from the intensity relations one can obtain the quantitative proportions of the components. If the crystal lattice is deformed by tension or by work done on the substance (for instance as in rolling or stretching, etc.), the position of the interference maxima is displaced in a characteristic way. From interference pictures produced we can deduce the size of the single crystallites in the metal.

The distances between the atoms contained in free molecules

can be measured by means of X-ray diffraction. It can be shown that even the moving molecules of gases have a clear diffraction effect. The measurement of distances between the atoms of a molecule is best carried out on the substance in gaseous form, since then interference phenomena arising from

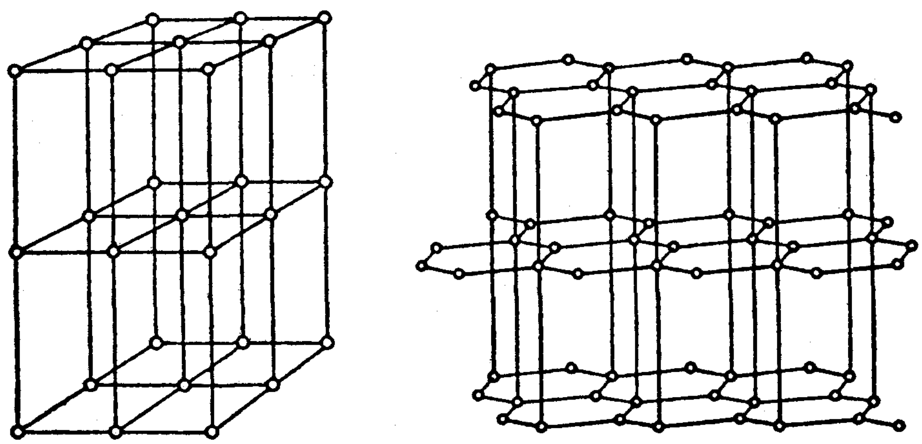

FIG. 30. Crystal gratings: (*a*) common salt, (*b*) graphite.

any regular arrangement of the molecules, as in a solid, do not occur. In a gas the molecules are, to all intents and purposes, in complete disorder (in an "isotropic" state).

In liquids the atoms are also not motionless. The liquid phase of matter must be placed between the isotropic and the crystalline (or "anisotropic") states. Any given atom of a liquid is surrounded by its neighbours with some degree of regularity which, however, is lost with increasing distance. The attractive forces between the molecules produce a form of order, the "quasi-crystalline" groupings, which through collisions with one another, due to the thermal motion, break up again and again, regrouping themselves momentarily. This formation of clusters can already be investigated by means of light optics. In contradistinction to quasi-crystalline fluids, amorphous substances, such as glass, the structure of which corresponds to an extraordinarily viscous fluid but not to a crystal, show the beginnings only of a lattice order. As far as light optics and X-ray optics are concerned, the amorphous body behaves completely isotropically.

Amongst the numerous properties of solid bodies, we wish to treat only two from the point of view of atomic physics: electrical conductivity and ferromagnetism.

Metals are distinguished by their ability to absorb and reflect light (lustre) and by their high conductivity of electricity and heat. All these properties are due to the same reason: the free mobility of the electrons. In a homopolar molecule bonds are produced owing to the fact that certain electrons are simultaneously revolving around more than one atomic nucleus. The metals are, so to speak, giant homopolar molecules consisting of 10^{20} or more atoms. In them, the electrons responsible for the bonding can wander freely through the entire piece of matter. If this constant, irregular wandering has a preferential direction imposed on it, it may be observed as an electric current. If the metal is given some disordered energy (heat), then the electrons quickly spread through the entire body. If light falls on to the metal from the outside, it produces sympathetic oscillations of the electrons. The latter quickly use up the energy of the light source. The oscillating electrons, however, re-emit a part of the energy as light; this is reflection.

Electrical resistance, as treated in Ohm's law, is due to the collisions of electrons with the atoms of the metal. In certain materials the resistance will disappear completely at very low temperatures ("superconductivity"). An induced current, once it is produced in a circular super-conducting wire, can continue in it for twenty-four hours or longer without any decay, if only the temperature is kept low enough. Presumably in superconductors numerous electrons mutually produce a sort of condensed electric fluid.

According to the theory of Weiss and Heisenberg, the magnetism of iron, cobalt and nickel also depends on the interaction of the electrons. The carrier of this magnetism is the spin of the electrons, mentioned briefly above, which at least perceptually if inaccurately, can be compared with a revolution of the electron around its own axis. Ampère's explanation that magnetism is due to circular atomic currents is thus justified in a certain sense.

Biophysics

The connection of physics with living matter is a fundamental question and one of the greatest significance. To enter

upon it, we should have to expand upon the problems of biology. This we cannot do here.

However, since all living bodies consist of the same chemical elements as those which we call non-living, and since all the known laws of inorganic chemistry, in so far as they can be at all verified experimentally, have always been shown to hold for the case of living organism, physics and chemistry must play an important role in biology, if only as auxiliary sciences. Certainly, some processes in living organisms can be observed physically and chemically and can be so influenced and interpreted.

Physical methods of observing and influencing organisms will be touched upon below. Amongst the many physical and chemical interpretations of life processes, beginning with anatomy and physiology, we shall look at only a single one which promises to produce a connection between biology and atomic physics.

The physical basis of inheritance can be investigated mainly in the chromosomes of the cell nuclei. We consider the individual hereditary traits as localised in certain parts of the chromosomes, the genes. Sudden changes of these traits (mutations) could then be reduced to changes in the genes. On the basis of comprehensive experiments, Timofejeff, Delbrück and Zimmer considered these changes as single quantum-mechanical elementary acts (for instance, rearrangement of an atom in a molecule). Thus it is possible that a gene itself must be considered as a single large molecule, and that our inability to make a prediction in which particular individual a certain mutation will take place is identical with the quantum mechanical uncertainty of atomic processes.

Other structures that can perhaps be considered as large molecules, are the units of the smallest infective organisms—viruses. They show, on the one hand, typical properties of living matter: the production of offspring similar to the parents, in which too, there can be mutations, and these in their turn are reproduced in further generations. On the other hand, viruses show typical molecular properties: fixed molecular weight and crystallisability. It is possible, that here there is a substance which proves directly that no sharp limit can be drawn between living and non-living matter.

Application

As long as chemistry has existed, mankind has unwittingly been making use of interactions between atomic shells. The various possibilities of the combinations of atoms into molecules were first derived from the different chemical compounds. With our knowledge of the structure of the atomic shell we can now explain the discovered laws, and we can interpret them fundamentally by referring both to the order of the shell electrons revolving round the atomic nucleus, and to electrical forces (*see* pages 135–136). Furthermore, our knowledge of the structure of chemical bonds has been an essential aid in preparative analytical chemistry, since it led to theoretical predictions of the given possibilities.

Those processes in the electron shell of the atoms which do not depend on interactions with other atoms are basically exhausted with the emission and absorption of electro-magnetic waves, especially of visible light and of X-rays, but also of γ-rays. Jumps of electrons of the outer shell into higher states of energy, or alternatively back to the original, absorb or create light quanta corresponding to Bohr's second postulate. If this rearrangement of electrons takes place in the inner shells, the energy change involved is generally higher and X-radiation takes place. The modern application of the properties of the atomic shell is primarily limited to finding suitable technical conditions for the optimal production of light energy (for instance in lamps), and for the production of light with definite wave-lengths.

The application of our knowledge of the properties of the atomic nucleus has taken place only in very recent times. Before 1945 the only nuclear processes exploited were those beyond human control, and present since the beginning of our world, such as the radiation of the sun and stars. Man first used his knowledge of the atomic nucleus and of its components in the irradiation and bombardment of matter with radio-active rays.

We already know that X-rays, when penetrating matter, are absorbed differently according to the density and the thickness of the material irradiated, and that they can thus be used for taking contrast pictures of use in medicine, and for non-destructive testing of material. In testing metal tubes, etc.,

for flaws, very energetic radio-active γ-rays are used, which are more convenient to handle. More recently we have learnt to build neutron point sources, so that we can irradiate matter with neutrons and thus make its structure visible. Neutrons are preferentially scattered by light atomic nuclei, so that the neutrons make visible quite different parts of the structure from, for instance, those revealed by X-rays.

It has been known for long that X-rays and γ-rays may alter the structure of the matter which they penetrate, especially in the case of living cells. The chief cause of these changes is always the ionisation which takes place when the rays penetrate matter. Therefore, in this respect the basic effects of all forms of radiation are similar. Different radiations as for instance, α-rays, deuterons, protons, mesons, and electrons are differentiated only by their ionisation strength and by the depth to which they can penetrate the material. The greatest penetrability for the lowest ionising power is found in the case of γ- and X-rays; neutrons, which may also have a considerable penetrability, do not ionise directly but only by means of the nuclei with which they collide. The immediately observable effects in biological materials, whose connection with ionisation has not been understood in every case, are the inhibition of growth, the destruction of cells and the production of mutations (*see* page 141). In inorganic materials, fluorescence can be produced which, for instance, can be used for demonstrating the presence of these particles, as with scintillation screens. The ionisation effect of the radiation can be used in technology for removing the electrical charges produced through friction, for instance when a thread runs on a spindle, etc.: here an equalisation of potential in the environment is produced by ionising the air around it, by means of α-rays.

The practical utilisation of atomic energy is always done through producing heat.

The emission of particles of high energy from radioactive substances and the re-coil of the nucleus can be observed as a heating effect on the environment—since increased energy of motion in the elementary particles means increase in temperature. The great quantity of heat produced by radioactive substances is best seen in the fact that the high temperature of the interior of the earth can be exclusively explained

in terms of the presence of radio-active substances; indeed, we must even conclude that inside the earth the percentage of radio-active substances is considerably less than at the surface, for otherwise temperatures would be too high even for the surface of our earth. The transformation and decay processes which in stars and the sun lead to the creation of helium from hydrogen nuclei, give the high energies which are required for the maintenance of the high temperature and the constant radiation into cosmic space. Heat is also the form of energy used in the uranium pile, where it is carried away by means of a heat-exchange liquid to the place of application, for instance to a boiler producing steam.

Much use has been made of the isotopes produced as a by-product of the transformation of elements into stable elements. These by-products can be detected even in the case of very extreme dilution by means of their radio-activity. The path and the corresponding time taken by ingested particles or of drugs in the human, animal or plant body, can be found by following the particles with a counter. The radio-activity of the added *indicator* is generally so small that it does not produce any damage to the organism. On the other hand, if a radio-active irradiation of a certain part of the body is desired, we can investigate which kind of atom is preferentially deposited there, and then add to the diet a radio-active isotope of this element, or a combination of it with a radio-active indicator; this will be deposited at the desired part of the body.

This indicator method can also be applied in technology. For instance, in the production of rayon fibres, carbon disulphide must be added to the alkaline cellulose of the fibres while the latter are being compressed through a very fine spinning jet. The whole of the sulphur must afterwards be washed out. If radio-active sulphur atoms (S^{35}) are added to the original sulphur, then any radio-activity remaining in the fibre after the bath would show that the bath has not done its work. In the dying of materials, the uniformity of the coloured layer can be controlled through the constancy of the activity of a small addition of a radio-active isotope. In a similar manner the strength of filters, the rate of diffusion, etc., can be determined. A further field of application is the testing of the

uniformity of mixtures and alloys through adding radio-active isotopes to one of the components. The enumeration of the many numerous technical possibilities of the indicator methods in industry and science would take us too far.

Natural radio-activity is used as an indicator mainly in geological investigation of bore-holes, and for detecting warps, fissures and fine structure. The age of rocks can be determined from the composition of the isotopes and the relationship of the mixture of the original products to the final element.

The use of a mixture of stable isotopes of an element, in a proportion different from the naturally occurring one, is suitable for investigations which take a long time, and is used when any effects of radio-active radiation are to be avoided. It is true that for detecting them a considerably greater quantity is required and the addition cannot take place in the form of traces, since the testing is only possible by means of the mass-separation of the isotopes (as, for instance in the mass spectrograph); for their relative proportions to remain easily measurable, isotopes would have to be present in a concentration of not less than 1 in 30,000. In the mass spectrograph, ions of the isotopes to be separated pass through a strong electric field in which they are accelerated. They then enter a magnetic field, the strength and geometrical arrangement of which is so chosen, that at any instant particles of equal mass are directed to the same points. The presence of ions is demonstrated by means of a photographic plate.

SUGGESTIONS FOR FURTHER READING

Text Books

NIGHTINGALE: *Higher Physics.*

STARLING and WOODALL: *Physics.*

GRIMSEHL: *Textbook of Physics.*

MARGENAU: *Physics: Principles and Applications.*

KRONIG: *Textbook of Physics.*

ABRAHAM and BECKER, W.: *Classical Theory of Magnetism and Electricity.*

SLATER and FRANK: *Introduction to Theoretical Physics.*

PLANCK, MAX: *Theoretical Physics.*

SOMMERFELD, A.: *Lectures on Theoretical Physics.*

LINDSAY and MARGENAU: *Foundations of Physics.*

Handbooks

GRAY: *Dictionary of Physics.*

GLAZEBROOK: *Dictionary of Applied Physics.*

KAY and LABY: *Tables of Physical and Chemical Constants.*

Historical

PLANCK, MAX: *Scientific Autobiography.*

LAUE, MAX VON: *History of Physics.*

TATON, R.: *Reason and Chance in Scientific Discovery.*

General Literature

BORN, MAX: *The Restless Universe.*

BROGLIE, L. DE: *Matter and Light.*
Physics and Microphysics.

EDDINGTON, A.: *The Nature of the Physical World.*
New Pathways in Science.
The Philosophy of Physical Science.

EINSTEIN, A., and INFELD, L.: *The Evolution of Physics.*

FARADAY, M.: *Experimental Researches in Electricity.*

HEISENBERG, W.: *Philosophic Problems of Nuclear Science.*
The Physicist's Conception of Nature.

JORDAN, P.: *Physics in the 20th Century.*

MARGENAU: *The Nature of Physical Reality.*

SCHRÖDINGER, E.: *Science and Humanism.*

UBBELOHDE, A. R.: *Man and Energy.*

WEIZSÄCKER, C. VON: *The History of Nature.*
The World-View of Physics.

ZIMMER: *The Revolution in Physics.*

Journals

Proceedings of the Physical Society, A and B.
Journal of Scientific Instruments.
Journal of Applied Physics.
Physical Review.
Nature.
Science Progress.
Science Abstracts.
Chemical Abstracts.

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